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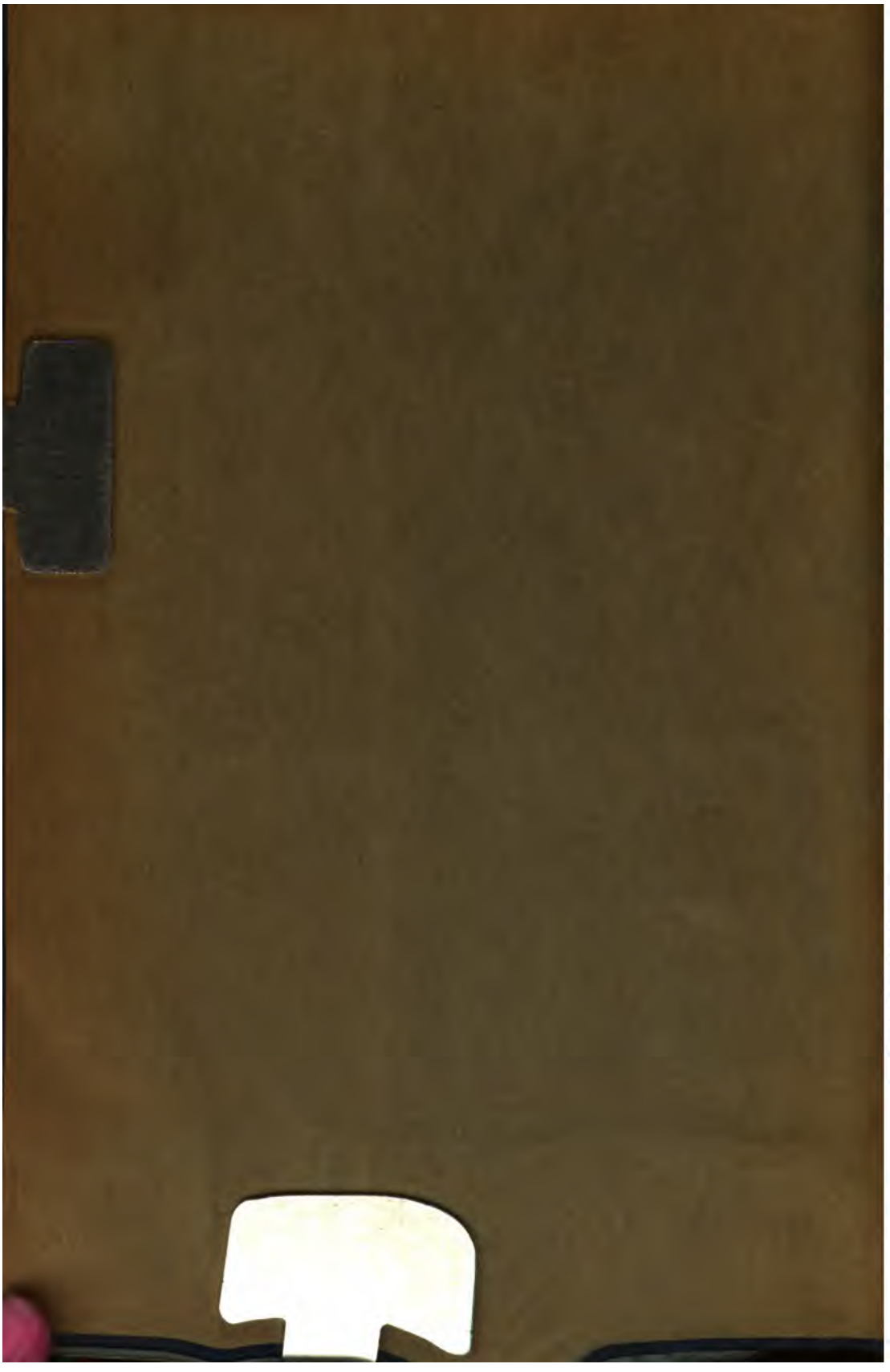

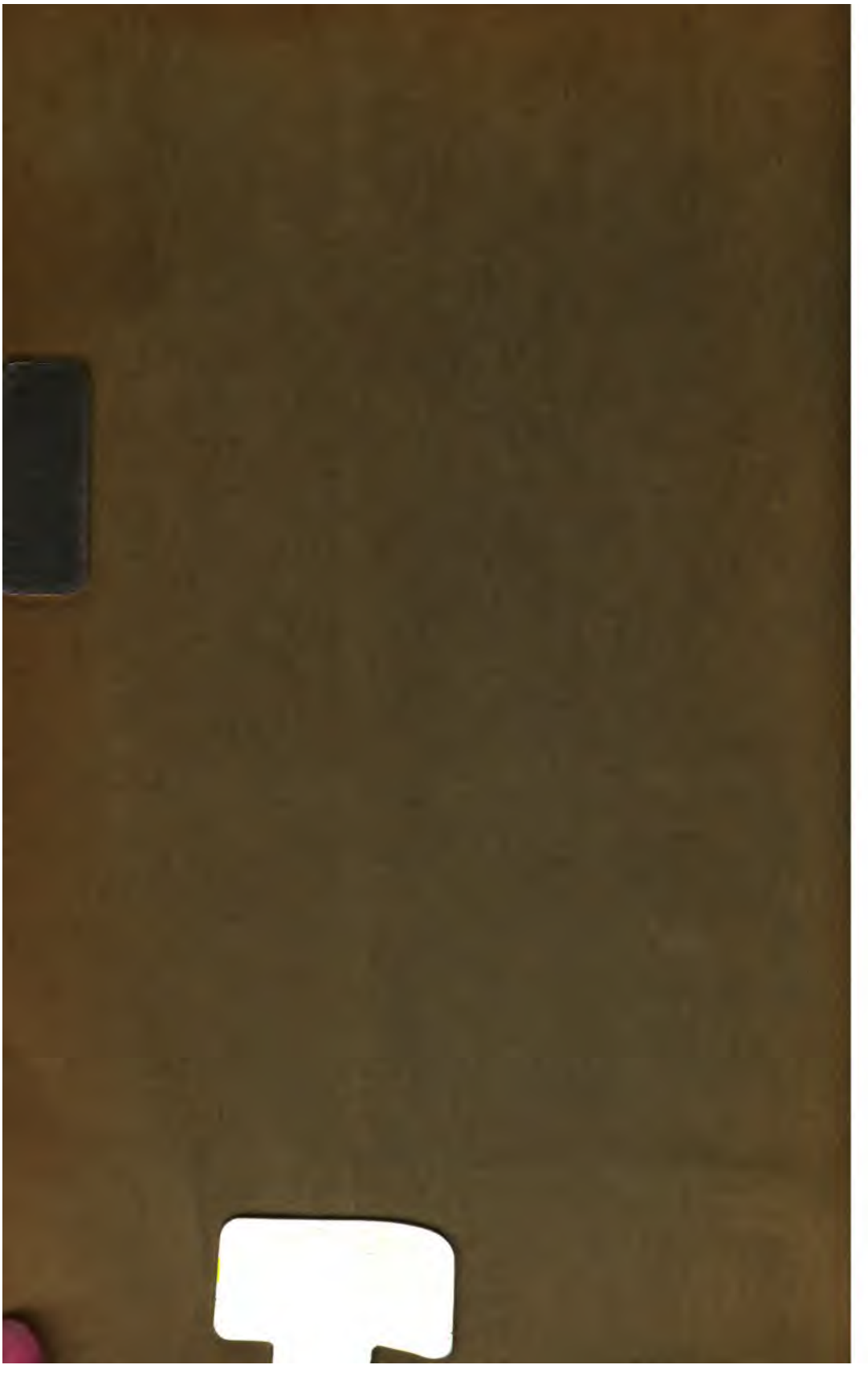

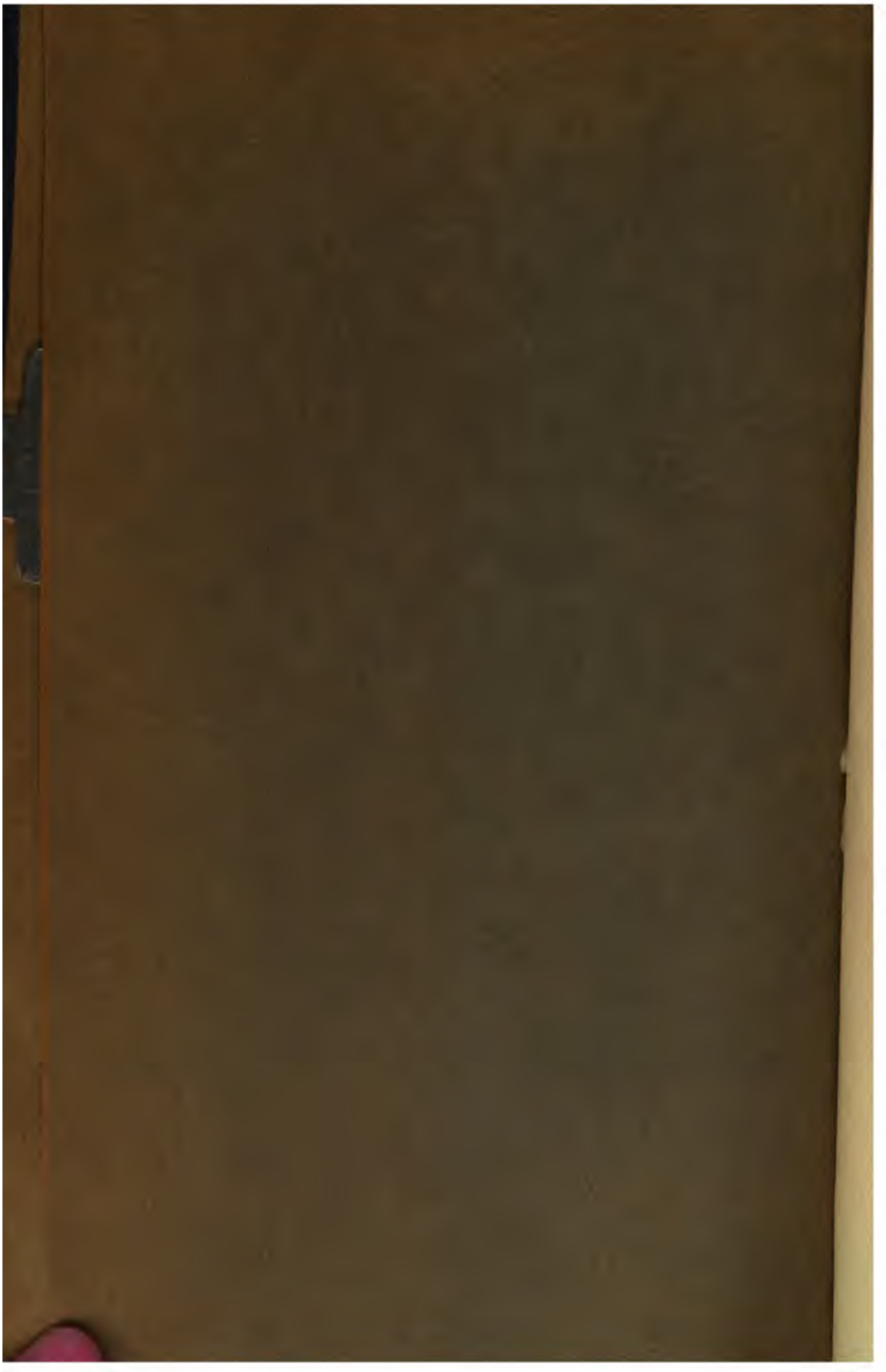

BOOKS ON

MODERN INDUSTRIALISM AND ITS RAW MATERIAL SUPPLIES

By EDWIN C. ECKEL

Cements, Limes and Plasters; their Materials, Manufacture and Properties. 8vo, 655 pages, 158 figures, 6 folding plates. John Wiley & Sons, New York, 2d edition, 1922. **$6.50** *net*

The Portland Cement Industry from a Financial Standpoint. 8vo, 93 pages, map, 4 figures. Moody Publishing Co., New York, 1908. *Out of Print.*

Building Stones and Clays; their Origin, Characters and Valuation. 8vo, 262 pages, 37 figures. John Wiley & Sons, New York, 1912. **$3.00.**

Iron Ores; their Occurrence, Valuation and Control. 8vo, 430 pages, 66 figures. McGraw-Hill Book Co., New York, 1914. **$4.00.**

Coal, Iron and War; a Study in Industrialism, Past and Future. 8vo, 375 pages, 9 figures. Henry Holt & Co., New York, 1920; Harrap & Co., London, 1921. **$3.00.**

CEMENTS, LIMES AND PLASTERS

THEIR MATERIALS, MANUFACTURE AND PROPERTIES

BY

EDWIN C. ECKEL, C.E.

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PREFACE TO SECOND EDITION.

In preparing the second edition of Cements, Limes and Plasters, the original work has been extensively revised, statistics and reference lists have been brought up to date, and about one hundred pages of entirely new matter have been added. In order to permit this, and at the same time keep the book within reasonable limits in size and price, the space formerly allotted to natural cement has been correspondingly reduced, as that industry is falling off in importance.

The chief additions have been in the sections devoted to Portland cement, to the gypsum products, and to the magnesian cements—all of these industries being still in rapid growth. The sections relating to raw materials of the various industries, to fuels, and to products have been thoroughly revised; and several hundred analyses have been added to cover points of special importance. Canadian and foreign developments have been given more space than in the earlier edition, since from now on the United States will of necessity be keenly interested both in foreign competition and in foreign markets.

In dealing with Portland cement the writer has drawn on a rather extensive experience, during the last fifteen years, in connection with various phases of that important industry, not only in the United States but in such diverse areas as Canada, France and Argentina. It is believed that the sections on raw materials, methods and costs will be found to contain data not obtainable in any other publication.

The attention of every reader is specially called to the Introduction of this edition. The matter there presented regarding the proper utilization of cost data, and the past and future trend of cost and prices, is of direct importance to each of the industries concerned.

EDWIN C. ECKEL.

WASHINGTON, D. C.,
April 5, 1922.

PREFACE TO FIRST EDITION.

Of all the non-metallic structural materials in use by the engineer, the most important at the present day are those included under the head of Cementing Materials, using that term in its broadest sense to include not only the hydraulic cements proper, but the limes, plasters and allied materials. This importance is due in large part to the advances which have been made, in American practice, in the methods of manufacturing these products, for these advances in technology have resulted in supplying the engineer with uniform and high-grade cementing materials at prices low enough to permit of great increase in their uses.

In consequence of this growth of the industries based on cementing materials an extensive literature on the subject has developed. This literature is, however, widely scattered through the pages of many technical and scientific journals and transactions, and no adequate summary of the matter from an American point of view has yet appeared. The present volume is the result of an attempt to provide such a summary, covering the composition and character of the raw materials, the methods of manufacture, and the properties of the various cementing materials.

In a work of this scope many points of interest can only be suggested, not discussed in detail. For the convenience of those who wish to make further studies of such subjects, very complete reference lists have been placed in almost every chapter of this volume. These lists necessarily contain the names of some papers and articles published in European periodicals or transactions, but most of the titles cited will be found to be from readily accessible American journals. A working engineer rarely has at his command an extensive technical library, so that references to the proceedings of some German scientific society are apt to prove a vexation rather than an aid.

Stress has been laid, in the discussion of manufacturing methods, on the general chemical and physical principles which underlie these methods rather than on the details which differ at every plant and may

change with every year. So far as possible, however, such details as bear on labor, power, and costs have been carefully discussed, and it is believed that the estimates furnished are entirely reliable.

The writer's acknowledgments are due to *Engineering News*, *Municipal Engineering*, *Engineering Record*, *Engineering and Mining Journal*, *Cement*, and *The Iron Age* for permission to use illustrations and to reprint parts of articles which had appeared first in their columns. To an even greater extent he is indebted to the chemists and managers of American cement-, lime-, and plaster-plants, and to manufacturers of different lines of machinery, for data and illustrations which they have kindly furnished for use in this volume.

It may not be out of place to state that this volume was planned and partly written in 1901. If it had been published at that date the words "probably" and "possibly" would not have occurred so frequently as they do in the present work, for at that time the writer felt a cheerful certainty in regard to many points which now seem less obvious. A wider personal experience, taken in connection with the remarkable changes which have recently affected both the theory and practice of cement-manufacture, has resulted in a more cautious treatment of certain phases of the subject.

EDWIN C. ECKEL.

WASHINGTON, D. C.,
March 6, 1905.

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CEMENTS, LIMES, AND PLASTERS.

INTRODUCTION.

THE present volume is devoted to consideration of the various cementing materials used by the engineer for structural purposes. With this broad use of the term, it includes not only the Portland, natural and puzzolan cements, but also the ordinary limes and the hydraulic limes, magnesia and its cementing products, and the gypsum plasters.

The technical importance of this group is evident, and some idea of of its commercial importance can be gained if we reflect that at present the world produces annually some fifty million tons of such materials, with a current total value of some three hundred million dollars. At the peak of high prices in 1920 it is probable enough that the annual world output of all kinds of cementing material would have showed a total value of close to five hundred million dollars. In future the total values may fall off for some time as the general price level moves irregularly downward. But the total tonnages produced will still increase from year to year, for the world market has not yet reached a permanent "saturation point" with regard to the demand for cementing materials. Both of these phases of the subject will be taken up later in more detail, in order that we may get a clear idea of the probable future of the industries with which this volume is concerned.

History of the Chief Cementing Materials.

At the outset we may glance over the history of the more important cementing materials, so far as that history is known, in order to secure a background against which our later discussions of growth and statistics will stand out more distinctly.

At the present day, when the Portland cement industry has attained such size and importance, it is natural enough to think of that particular kind of cement as the typical representative of the group; and it is difficult to realize that it is almost, if not quite, the most modern of all the cementing materials. The Portland cement industry is still less than a

century old, and its period of really rapid growth did not commence until within the past thirty years. During all the earlier periods of human history engineering structures were made with the help of other types of cementing materials, some closely allied to Portland cement, others differing widely from it, but all serving the purpose of the engineer with more or less efficiency.

Of the seven classes of cementing materials discussed in the present volume, two date back to the remotest periods of antiquity. There does not seem to be the slightest evidence that truly hydraulic cements of the kinds we now use were ever employed by the older Asiatic, Egyptian or east Mediterranean civilizations. On the other hand there is direct proof that at a very early stage of human progress, say ten thousand or more years ago, both lime mortars and gypsum plasters were put to use in Egypt and elsewhere. But even these two types of cementing material were in the early stage, used in most cases as coatings or plasterings, rather than as binding material for the masonry.

At a considerably later stage in history we find that the Romans, in addition to employing lime mortars and gypsum plasters, also made use of the earliest type of puzzolan cement. This was made from pozzuolana, a volcanic ash that is found abundantly in the vicinity of Naples; and at a very early date in Roman history this ash was powdered, mixed with quicklime, and used for work under water. This use of pozzuolana has persisted to the present day, and the ash has given its name to the entire group of *puzzolan cements*, but as will be seen later the best-known modern representative of that group is not made from volcanic ash but from blast-furnace slag.

During the Middle Ages, along with the general retrogression in technical knowledge, the use even of these primitive puzzolan cements seems to have been discontinued except perhaps in Italy itself. The material employed for holding masonry together in large structural work was plain lime mortar, though by using an abundance of time and taking great care in the preparation of the lime and the mortar, structures of remarkable strength and durability were finally developed. At a few places in Europe, where naturally impure limestones existed, the lime made from them must necessarily have had the property of setting under water like a cement. But when this occurred it was an accident, and there is no evidence that any attempt was made to intentionally select limestone whose product had this property. The sporadic instances of the occurrence and use of what may be considered a low-grade natural cement should not be allowed to obscure the fact that all of the great cathedrals, fortresses and other structures of the Middle

Ages were built with common lime as a mortar. This practice, indeed, continued down to near the close of the eighteenth century, when an entirely new series of cements were invented and perfected. These, under the names of natural or Rosendale cements, have continued in use until the present day.

The natural cements, made by burning a clayey limestone, came into use during the closing years of the eighteenth century and the early years of the nineteenth, when along with the other features of the Industrial Revolution there was brought about the development of the navigable canal system in England and elsewhere, with its necessary requirement for a really hydraulic cement.

Portland cement, now the most important of our cementing materials, was invented in 1825, and was thus contemporary with the first railway, and the first ocean steamship, while it antedated by some thirty years our two important structural steels—Bessemer and open-hearth.

The magnesian or oxychloride cements came to light still later in the nineteenth century, while the use of blast-furnace slag as a cement material is of relatively recent date.

On later pages where the different cementing materials are separately discussed, more detailed data are presented relative to their history and industrial growth. The present summary is designed merely as an outline of the more important facts. It will have served a good purpose if it calls attention to two matters of general industrial importance. The first of these is that at different times the engineers of the world have used different cementing materials, and that the widespread use of a certain cement for a long period did not imply that no successor or alternative cement was possible. The second is, that the invention of the different cements was not an accidental or sporadic occurrence, but was related closely to the industrial activities and requirements of the period in which the invention took place.

Relative Importance and Growth.

Having outlined the manner in which the different cementing materials have, at different periods, come successively into engineering use, we may now pay some attention to their relative rank or importance as engineering materials, and to their comparative growth in such importance during recent years.

In selecting the dates for these comparisons, the decade 1903–1913 presents certain advantages, and avoids certain difficulties. It gives a ten-year record of growth, during a period in which all the world was prosperous. It avoids entering upon the period of madness, industri-

ally considered, which came to us with the outbreak of the World War. The year 1913 was the last year of normal business conditions in any industry and in any country. Records for subsequent years would be vitiated, for comparative purposes, because from 1914 to 1921 inclusive industries everywhere were subjected either to unnatural stimulus or to equally unnatural repression; while values stated in terms of any currency fluctuated, not with business conditions, but with variations in government credit and circulation.

Production in the United States.—The following short table summarizes the outputs of the various cementing materials in the United States during the years 1903 and 1913 respectively.

TABLE 1.

TONNAGE OF CEMENTING MATERIALS PRODUCED IN UNITED STATES, 1903–1913.

Class of Material.	Output, 1903.	Output, 1913.
Portland cement	4,244,600	17,498,430
Gypsum plasters	952,543	1,908,157
Building lime	1,000,000	1,358,099
Magnesia	47,208	183,570
Natural cement	931,510	98,667
Puzzolan cement	78,962	17,707
Total tonnage cementing materials	7,254,823	21,136,630

These figures become of more service if we use them to establish the rate at which the various groups increased in output during the decade in question. This gives the following results:

INCREASE OR DECREASE DURING DECADE.

Portland cement	Increase 312 per cent
Magnesia	Increase 289 " "
Gypsum plasters	Increase 108 " "
Building lime	Increase 36 " "
Puzzolan cement	Decrease 78 " "
Natural cement	Decrease 89 " "
Average all classes	Increase 191 per cent

The remarkable nature of this rate of increase is not understood until we compare it with that shown, during roughly comparable periods, by certain better-known mineral industries. The necessary data for these comparisons are fortunately available, having been prepared recently for use in another connection.*

* "Coal, Iron and War," pp. 120, 217, 313.

Taking the four other leading industries of this general type, during decades just before the war, so as to avoid the effects of the war itself, we find that their percentages of increase in output per decade were as follows:

World output of coal, from 1900 to 1910 increased.....	51 per cent
World output of pig-iron, from 1900 to 1910 increased...	62 " "
United States output of sulphuric acid, from 1904 to 1914.	93 " "
World output of petroleum from 1900 to 1910 increased.	120 " "
United States output of cementing materials from 1903 to 1913.....	191 " "

It might be added that, if in place of using the 1913 figures in making these comparisons, we made use of those for 1919 or 1920, the results would merely become more emphatic. We would see an even greater rate of increase in the cementing materials as a group. And we would see, still more clearly, that this total increase is due to the growth of the Portland cement, magnesia and gypsum plaster industries. Limes have not much more than held their own for a decade past; while the pùzzolan and natural cements have actually fallen off in output, and fallen off very rapidly.

Relation to population.—The data as to output of cementing materials in the United States and Canada may be made still more interesting and useful if we consider them in relation to the population of the two producing countries. This comparison, for the 1913 output in each case, gives the following results:

CEMENTING MATERIAL OUTPUT PER CAPITA, 1913.

	United States.	Canada.	Average.
Production, tons per capita.....	0.195 ton	0.29 ton	0.20 ton
Value, dollars per capita.....	$1.01	$1.67	$1.05

These comparisons are of special interest because we are dealing with countries which, though at an advanced stage of civilization, were still in process of rapid growth at the period under consideration. They were, in 1913, prosperous and sound financially, both as regards private and government finances, so that new enterprises and new construction could be readily handled. The results as to structural material consumption have therefore a very distinct value, which is increased by the fact that neither country had, in 1913, any serious export or import trade in these commodities. We may accept the averages in the last

column, therefore, as being fairly representative of this grade and type of community during the last years before the World War.

In the years after 1913 the cementing material outputs varied with general trade conditions, but owing to their heavy fuel consumption and the fact that most of their products were not of direct military necessity the output did not increase as rapidly as did that of certain more immediately necessary products such as the materials used in munitions manufacture or in armament. Nevertheless there was a gain, not only in total output but in output per capita; and at the height of the war-boom it is probable that American and Canadian output reached close to one-quarter ton per capita. This figure may be looked upon as a temporary maximum, but it will be exceeded during the next period of business prosperity.

The general trend of costs and prices.—The first edition of this book was written at a time when, for a decade or so, the general price level was relatively stable, so that the costs and prices of cementing materials could be discussed individually, without paying much attention to broader price movements. But as we all know now, that condition of stability is far from being the case at present, and we can make no serious use of existing statistics, and no prediction as to the future, unless we keep general conditions clearly in mind. For this reason a brief discussion of the trend of costs and prices is inserted here; the reader who is interested in a more detailed discussion of these subjects is referred to a recent volume * in which they are more adequately treated. Here we will consider the matter with special reference to the industries which are the immediate subjects of this volume, and with the idea of making it possible to utilize, under present and future conditions, the statistical data already on hand.

Judging the known conditions in the light of past experience, we may safely conclude that:

(1) Average prices will fall, on the whole for perhaps the next twenty or thirty years, so that the price level of 1950 may be substantially that of 1900. This fall would be checked or reversed only by some widespread cause of inflation such as another great war.

(2) The fall in prices will, however, not be regular or continuous. It will proceed in great cycles, of rapid fall followed by partial recoveries. These minor price cycles will be made up of alternating periods of business prosperity and of business depression, as we have always experienced. But the high points (of price averages) reached during pros-

* Eckel, E. C. Coal, Iron and War; a Study in Industrialism Present and Future. 8vo, 375 pp. New York, 1920; London, 1921.

perous periods will not be as high as we have just experienced; while the low averages during the depressions will tend to become successively lower.

(3) With regard to any particular commodity, its costs and price will vary in part with the trend of average prices, and in part with the condition within the particular industry in question.

The proper use of cost and price data.—With the preceding general discussion as a basis, we may now turn to consideration of how these facts can be utilized in our immediate study. This can be done most simply by using the average price index presented here in Table 2 as a means of reducing the figures of cost and price for any given year to current values.

TABLE 2.

AVERAGE WHOLESALE COMMODITY PRICES, 1890–1920.

Year.	Index Number.	Year.	Index Number.	Year.	Index Number.
1890	84	1901	81	1911	96
1891	84	1902	84	1912	100
1892	79	1903	85	1913	101
1893	79	1904	84	1914	100
1894	72	1905	87	1915	101
1895	70	1906	92	1916	124
1896	67	1907	97	1917	176
1897	67	1908	92	1918	196
1898	69	1909	95	1919	212
1899	76	1910	99	1920	244
1900	83				

The trend of cementing materials costs and prices.—The data and principles stated above may now be applied more directly to the cementing materials industries.

Here in each case we are dealing with a natural raw material, transformed into a finished product by the use of fuel, machinery, labor and brains. The trend of costs and prices in these industries will in future vary with (1) the trend of general or average prices and (2) changes in the particular elements of cost of the industry itself. The first factor has been discussed in the preceding section; it is concluded that general or average commodity prices will fall irregularly for very many years. The second factor may now be considered.

Of the elements of cost in making and marketing lime, plaster or cement, that of raw material is likely to have little influence on future costs. The raw materials used—limestone, clay, shale, gypsum, etc.—are all present on this earth in very large quantities indeed; and there

is no chance that, except locally, the supplies will become exhausted or so scarce as to tend to raise costs.

With regard to fuel, this is not the case. It is certain that in future we will pay more for coal and oil than we have in the past, regard being had of course to the general price level. Each year our coal mines are becoming deeper; each year a little poorer and thinner coal is being mined; and these conditions will become more noticeable every decade. Further than that, the steady increase in labor organization in the coal regions implies a higher labor cost per ton of product. And the known situation with regard to oil supplies does not offer much hope of relief from that source.

The machinery and appliances used in the mills are made chiefly from two metals which, like coal, seem to have passed their maximum of commonness, and which are equally likely to be somewhat dearer in future than in the past, relative to the general price level. Neither our iron ores nor our copper ores are as yet near exhaustion, but they are not as cheaply secured as a decade ago.

With regard to mill labor, the case is becoming clear enough. During periods of business depression there may be temporary falls in wages, but year in and year out the tendency is unmistakably the other way.

Of the four factors so far mentioned, that of raw materials is negative, while the other three suggest that the costs and prices of cementing materials are not likely to fall as fast as does the average price level; and that during upward movements in the average the cementing material figure will rise a little faster than the average. As against this tendency we have only the last factor available—the utilization of intelligence more completely. It is by way of new or improved processes only that the upward tendency in costs can be held in check.

Fortunately for the cementing materials industries, their chief competition in structural lines will suffer from at least equal disadvantages. Wood is reaching a condition of absolute natural scarcity, while steel costs rise as coal and labor become dearer.

Classification and Relationships of Cementing Materials.

It seems desirable, before taking up the various classes of cement materials individually, to indicate briefly the relationships that exist between the different classes which compose this group.

These relationships, as regards both resemblances and differences, seem to be best brought out by the scheme of classification presented

below. This classification was first published by the writer in 1902 * in a form differing but slightly from that here given. It is based primarily upon the amount of chemical change caused by the processes of manufacture and use; and secondarily upon the chemical composition of the cementing material after setting. As regard is paid to both technologic and commercial considerations, it would seem to furnish a fairly satisfactory working classification. For convenience of reference the pages on which the different products are discussed in the present volume have been added to the classification.

Classification of Cementing Materials.

Group I. Simple Cementing Materials: including all those cementing materials which are produced by the expulsion of a liquid or gas, through the action of heat, from a natural raw material, and whose setting properties are due to the simple reabsorption of the same liquid or gas, and the reassumption of original composition; the set cement being, therefore, similar in chemical composition to the raw material from which it was derived.

Subgroup I a. Hydrate Cementing Materials or Plasters: manufactured by driving off water from gypsum; setting properties due to the reabsorption of water.

Plaster of Paris,
Gypsum plasters, } pp. 18 to 74.
Cement plasters,
Dead-burned plasters, pp. 75 to 77.
Hard-finish plasters, pp. 78 to 80.

Subgroup I b. Carbonate Cementing Materials or Limes and Magnesia: manufactured by driving off carbon dioxide from limestone or magnesite; setting properties due to the reabsorption of carbon dioxide.

Limes, pp. 91 to 148.
Magnesia, pp. 149 to 171.

Group II. Complex Cementing Materials: including all those cementing materials whose setting properties are due to the formation of entirely new chemical compounds during manufacture or use; the set cement being, therefore, different in chemical composition from the raw material or mixture of raw materials from which it was derived.

Subgroup II a. Silicate Cementing Materials or Hydraulic Cements: setting properties due entirely or largely to the formation of silicates during the processes of manufacture or use.

* Eckel, E. C. The classification of the crystalline cements. American Geologist, vol. 29, pp. 146–154. March, 1902.

Hydraulic limes, pp. 72 to 199.
Grappier cements, pp. 189 to 193.
Natural cements, pp. 200 to 267.
Portland cement, pp. 268 to 574.
Puzzolan cements, pp. 575 to 632.

SUBGROUP II b. OXYCHLORIDE CEMENTING MATERIALS: setting properties due to the formation of oxychlorides.

Magnesia cements, Sorel stone, etc., pp. 149 to 171.

The Choice of Cementing Materials.

In considering the mass of data which is now available regarding the properties of the various cementing materials, there is difficulty in sorting out just those facts which are necessary in choosing between the different classes for different kinds of work. I have therefore prepared a brief summary of those facts for insertion here, which I hope will be of service to some of my readers. So far as known, no engineering text-book gives exactly this sort of information, arranged in compact fashion; and of course the comparisons made in the advertising literature of manufacturers and dealers are to some extent subject to suspicion. It is possible that my own summary contains some errors of either fact or judgment, but it is at least free from considerations of personal interest.

In choosing the kind of cementing material that should be used for a particular purpose, the choice is oftentimes very clear. Commonly it will be obvious enough that a Portland cement, let us say, must be used; and then the only questions will be as to brand and price, neither of which are subjects for consideration here. But at other times there will be more latitude for choice; or perhaps more specialized requirements to be met. In such cases the data summarized below may be serviceable. They are arranged under certain headings which seem to be of the most general interest.

Cheapness of cement.—Based upon the usual average cost per ton of the crude cementing material itself, those in common use rank about as follows, from cheapest to dearest; (1) ordinary gypsum plaster, (2) ordinary quicklime, (3) hydraulic lime, (4) natural cements, (5) grappier cements, (6) slag and other puzzolan cements, (7) fused high-alumina Portland cements, (8) normal Portland cements, (9) high-iron Portland cements, (10) magnesia oxychloride cements.

Cheapness of mortar.—The cheapness of the mortar in which form the cementing material will probably be actually used, will depend of course only in part upon the cost of the crude or neat cement per ton. It will depend in larger part upon the sand-carrying capacity of the

cement. From this standpoint the rank of the different materials is about as follows, beginning with those which have the greatest sand-carrying capacity: (1, 2, 3) all the forms of Portland cement—whether normal, high-iron or high-alumina, (4) grappier cements, (5) slag cement, (6) natural cements, (7) hydraulic limes, (8) ordinary limes, (9) gypsum plasters and (10) magnesia cements.

Quickness of hardening.—Occasionally, in the course of construction or repair work, the matter of quick hardening is a factor in the choice. From this standpoint the different materials rank about as follows: (1) magnesia oxychloride cements, (2) gypsum plasters, (3) high-alumina Portlands, (4) normal Portlands, (5) high-iron Portlands, (6) natural cements, (7) grappier cements, (8) slag cements, (9) hydraulic limes, (10) ordinary limes.

Color of cement.—For some kinds of work the color of the cement is a matter of interest, either on its own account or because a light-colored cement will take other tinting better than a dark product. From this standpoint there are a number of materials which are normally light colored, and can be easily made white or nearly so at no expense; these white or whitish cements include the gypsum plasters, the magnesia cements, the ordinary and hydraulic limes, the grappier cements and the high-alumina Portlands. Slag cement is next in lightness of color; and after this comes the average normal Portland. The darkest products are the natural cements and the high-iron Portlands.

Engineering constructions.—When we limit the matter to engineering structures of ordinary type certain of the cementing materials are necessarily dropped from consideration. The magnesia cements are too dear; the ordinary limes and gypsum products are chiefly of use as plasters and not as mortars or in concrete. That still leaves, however, a field of choice far larger than the average American engineer is accustomed to considering. For in this country we have, for good or ill, concentrated on one of the best of the cements and left the others practically or entirely unused. Engineers in other countries are not quite so rigid in their ideas of utility and economy; and for that reason, since American engineers are likely to meet foreign competition in work abroad, it is worth while speaking of these other products.

For all reinforced work we may take it for granted that a normal Portland cement will be used everywhere; the other types are barred out from this important field for one reason or another. For all work which must be put in use promptly, we are also limited to either a normal or a high-alumina Portland.

These two classes cover perhaps two-thirds of all modern engineering

work. For the remaining third—mass concrete which is not in a hurry—there are several alternatives, all more economical than Portland cement, in the countries where these other products are made, because they are all less costly in the way of fuel used in their manufacture. Reference is made particularly to the important groups of hydraulic lines and grappier cements; their results in long-time tests are discussed later, and seem to justify their use for a wide range of work. They are not better than Portland but they are cheaper at their points of origin; so that for work in Europe or in South America the engineer will do well to keep the possibility in mind. For the United States and Canada it is not even a possibility; we have concentrated on normal Portland cement, we make it very good and fairly cheap, and we can not be drawn into any other line of activity. The development here is likely to be along the line of producing an even higher grade of Portland cement, rather than by taking up the manufacture and use of other kinds of cements.

Chemical, Physical and Geologic Data.

In the course of the present discussion reference will be made frequently to certain chemical, physical and geologic facts. All of the data necessary for these discussions will of course be found in ordinary text-books, but for convenience a few of the most necessary matters are briefly summarized here.

The chemical elements.—In Table 3 following the chemical elements are listed with their atomic weights. These elements that appear normal in cements, limes plasters, slags, fuels, etc., are given in black-faced type for convenience of reference.

Heat-units.—Two heat-units are now in common use—the British and the metric.

The British thermal unit (=B.T.U.) is the quantity of heat required to raise the temperature of 1 lb. of water one degree Fahrenheit when at the temperature of maximum density (=39.1° F. or 4° C.).

The metric unit (=calorie) is the quantity of heat required to raise the temperature of 1 kilogram of water one degree centigrade when at the temperature of maximum density.

From these definitions the two units may be converted according to the following equations:

1 B.T.U. = .252 calorie.
1 calorie = 3.968 B.T.U.
1 calorie per kilogram = 1.8 B.T.U. per pound.

TABLE 3.

ATOMIC WEIGHTS OF ELEMENTS

Name of Element.	Symbol.	Atomic Weight. O = 16.	Atomic Weight. H = 1.	Name of Element.	Symbol.	Atomic Weight. O = 16.	Atomic Weight. H = 1.
Aluminum	**Al**	**27.1**	**26.9**	Neodymium	Nd	143.6	142.5
Antimony	Sb	120.2	119.3	Neon	Ne	20.0	19.9
Argon	A	39.9	39.6	Nickel	Ni	58.7	58.3
Arsenic	As	75.0	74.4	**Nitrogen**	**N**	**14.04**	**13.93**
Barium	Ba	137.4	136.4	Osmium	Os	191.0	189.0
Bismuth	Bi	208.5	206.9	**Oxygen**	**O**	**16.00**	**15.88**
Boron	B	11.0	10.9	Palladium	Pd	106.5	105.7
Bromine	Br	79.96	79.36	**Phosphorus**	**P**	**31.0**	**30.77**
Cadmium	Cd	112.4	111.6	Platinum	Pt	194.8	193.3
Cæsium	Cs	132.9	131.9	**Potassium**	**K**	**39.15**	**38.85**
Calcium	**Ca**	**40.1**	**39.7**	Praseodymium	Pr	140.5	139.4
Carbon	**C**	**12.0**	**11.91**	Radium	Ra	225.0	223.3
Cerium	Ce	140.25	139.2	Rhodium	Rh	103.0	102.2
Chlorine	Cl	35.45	35.18	Rubidium	Rb	85.5	84.9
Chromium	Cr	52.1	51.7	Ruthenium	Ru	101.7	100.9
Cobalt	Co	59.0	58.57	Samarium	Sm	150.3	149.2
Columbium	Cb	94.0	93.3	Scandium	Sc	44.1	43.8
Copper	Cu	63.6	63.1	Selenium	Se	79.2	78.6
Erbium	Er	166.0	164.7	**Silicon**	**Si**	**28.4**	**28.2**
Fluorine	F	19.0	18.9	Silver	Ag	107.93	107.1
Gadolinium	Gd	156.0	154.8	**Sodium**	**Na**	**23.05**	**22.88**
Gallium	Ga	70.0	69.5	Strontium	Sr	87.6	86.94
Germanium	Ge	72.5	72.0	**Sulphur**	**S**	**32.06**	**31.82**
Glucinum	Gl	9.1	9.03	Tantalum	Ta	183.0	181.6
Gold	Au	197.2	195.7	Tellurium	Te	127.6	126.6
Helium	He	4.0	4.0	Terbium	Tb	160.0	158.8
Hydrogen	**H**	**1.008**	**1.000**	Thallium	Tl	204.1	202.6
Indium	In	115.0	114.1	Thorium	Th	232.5	230.8
Iodine	I	126.97	126.01	Thulium	Tm	171.0	169.7
Iridium	Ir	193.0	191.5	Tin	Sn	119.0	118.1
Iron	**Fe**	**55.9**	**55.5**	**Titanium**	**Ti**	**48.1**	**47.7**
Krypton	Kr	81.8	81.2	Tungsten	W	184.0	182.6
Lanthanum	**La**	138.9	137.9	Uranium	U	238.5	236.7
Lead	**Pb**	206.9	205.35	Vanadium	V	51.2	50.8
Lithium	Li	7.03	6.98	Xenon	Xe	128.0	127.0
Magnesium	**Mg**	**24.36**	**24.18**	Ytterbium	Yb	173.0	171.8
Manganese	**Mn**	**55.0**	**54.6**	Yttrium	Yt	**89.0**	**88.3**
Mercury	Hg	200.0	198.5	Zinc	Zn	65.4	64.9
Molybdenum	Mo	96.0	95.3	Zirconium	Zr	90.6	89.9

Metric conversion tables.—Since much of the literature of cementing materials is published in French and German, metric units are frequently employed. In the present volume such units have been converted into American units throughout, but for convenience a few conversion tables are here inserted to cover the more common cases.

LENGTH.

1 inch	= 2.54 centimeters.
1 centimeter	= .3937 inch.
1 foot	= .3048 meter.
1 meter	= 39.37 inches.
	= 3.2808 feet.

SURFACE.

1 square inch	= 6.452 square centimeters.
1 square centimeter	= .155 square inch.
1 square foot	= .0929 square meter.
1 square meter	= 10.764 square feet.

VOLUME.

1 cubic inch	= 16.387 cubic centimeters.
1 cubic centimeter	= .061 cubic inch.
1 cubic foot	= .02832 cubic meter.
1 cubic yard	= .7645 cubic meter.
1 cubic meter	= 35.314 cubic feet.
	= 1.308 cubic yards.

WEIGHT.

1 ounce avoirdupois	= 28.35 grams.
1 pound	= .4536 kilogram.
1 kilogram	= 2.2046 pounds.
1 metric ton	= 2204.6 pounds.

CAPACITY.

1 cubic foot	= 28.317 liters.
1 liter	= 61.023 cubic inches.
	= .03531 cubic foot.
1 gallon	= 3.785 liters.

PRESSURE.

1 pound per square inch = .070308 kilogram per square inch.

1 kilogram per square centimeter = 14.223 pounds per square inch.

Main classes of rocks.—Rocks are classified, according to origin, as either (1) *igneous* or (2) *sedimentary*. Usually it is easy to determine in which of these two classes a given rock should be placed, but as later noted there are times when such determination is very difficult or impossible.

The *igneous* rocks are those which have been formed by the cooling of fused material. The original crust of the earth was of course formed entirely of igneous rocks, but it is highly improbable that any of this original crust is still exposed at the earth's surface. The igneous rocks which we encounter now are of much later age, being derived from molten material which has at various times been forced up into and through other rocks.

The *sedimentary* rocks are those which have been derived from the decay or weathering of pre-existing strata, the loose material so freed being carried off (usually by running water) and finally deposited (usually in an ocean or other water-basin) as a bed of sand, clay, shells, etc. Later this loosely deposited material has been hardened by pressure or other agencies, so that finally beds of sandstone, shale, and limestone are formed.

Igneous rocks.—The igneous rocks differ among themselves in chemical composition, in mineral composition, in texture and in the details of origin; and they may accordingly be classified on any one of these bases. But for our present purposes these matters may be passed over briefly, for the igneous rocks are of interest to the cementing material industries in only a few relations.

Most igneous rocks cooled slowly below the earth's surface, and in consequence their constituent minerals crystallized out definitely. Among such massive and more or less coarsely crystalline igneous rocks may be noted the granites, syenites, gabbros, etc. Rocks of this type are of present interest chiefly because they are much used as concrete aggregates. A further special interest arises from the fact that most commercial magnesite deposits are associated, as secondary products, with certain very basic igneous rocks, high in iron, lime and magnesia, and low in alumina and silica.

Of the igneous rocks which cooled at or near the surface, one group has interest in the present connection. This includes the traps and basalts, very extensively used as concrete aggregates and later mentioned as occasionally being second-class puzzolanic materials.

Finally, the igneous rock material ejected from volcanoes does possess special importance to the cement technologist. The *volcanic ash* thus formed is almost invariably a puzzolanic material of high-grade,

whether it forms deposits on a land surface, or falls into a sea or lake basin to form a *tuff*.

Sedimentary rocks.—Though the igneous rocks are of slight importance in cement manufacture, the sedimentary rocks are of great importance indeed, for they furnish all of the limestone, clay, shale and gypsum used in the industries. For this reason somewhat more attention must be paid to them in the present place.

It has been said previously that the material making up the sedimentary rocks was derived ultimately from the waste or decay of preexisting rock strata. To this we may add that such waste material may have been carried away either mechanically, as suspended fragments; or chemically, in dissolved form. In either case the transporting agent was, in most cases, running water on the earth's surface; and in most cases the material so transported, whether carried in suspension or in solution, was finally deposited in an ocean, a lake or other water-basin.

So much being assumed, another stage in the process affords a convenient basis for classifying the sedimentary deposits; and this basis—the method of deposition—has been used in the summary following.

Classification of Sedimentary Rocks.

1. *Mechanical sediments*, composed of material transported in suspension, and deposited by gravity when the transporting water loses speed. This group includes the sandstones, conglomerates, clays and shales; of which the last two are of interest to the cement manufacturer.

2. *Chemical deposits*, composed of material carried in solution and deposited because of evaporation or chemical agencies. This group includes gypsum deposits and many limestones.

3. *Organic deposits*, composed of material carried in solution or gaseous form and deposited through action of organisms, either plant or animal. This group includes such diverse products as coal, oil, gas, diatomaceous earth; and also many limestones.

Geologic chronology.—By the application of various criteria, the relative ages of different series of rocks can be determined with considerable certainty. Such studies, carried on over most of the inhabited portions of the earth, have resulted in a grouping of rocks according to their ages, and a fairly complete geologic chronology has gradually been worked out so as to cover the whole extent of earth history. Our present interest in this phase of geology arises from the fact that, in consulting many of the reports listed in the bibliographies scattered through this

volume, the reader will find certain of these age terms used, often without definition or explanation. The brief summary which follows may be of service in such cases.

For convenience of reference and comparison, all of geologic time is primarily divided into four main time divisions. These are subdivided into twelve *periods*, which in turn are subdivided into *epochs*. Still more minute subdivisions are called *stages*, while the final unit of division is the *formation*. The names assigned to the *formations* are essentially local, and may vary from area to area; so that no general statement can be made concerning them. The periods and epochs, on the other hand, are time divisions world-wide in scope and these broader groupings can profitably be named here.

In the summary below the names of the periods are given in order downward from the most recent (Quaternary) to the oldest (Archæan). In some instances the subdivisions into epochs are also given.

	Period.	Epoch.
Cenozoic	Quaternary	Recent
		Pleistocene
	Tertiary	Pliocene
		Miocene
		Oligocene
		Eocene
Mesozoic	Cretaceous	
	Jurassic	
	Triassic	
Paleozoic	Carboniferous	Permian
		Pennsylvanian or Coal Measures
		Mississippian or Subcarboniferous
	Devonian	
	Silurian	
	Ordovician	
	Cambrian	
Pre-Cambrian	Algonkian	
	Archæan	

PART I. PLASTERS.

CHAPTER I.

COMPOSITION, DISTRIBUTION, AND EXCAVATION OF GYPSUM.

THE mineral called *gypsum* is the raw material which serves as the basis for the manufacture of plaster of Paris, "cement plaster," and the various related types of plasters. In the present chapter the composition, properties, varieties, mode of occurrence, origin, and distribution of gypsum will be described in the order named, after which the methods and costs of quarrying and mining gypsum will be discussed.

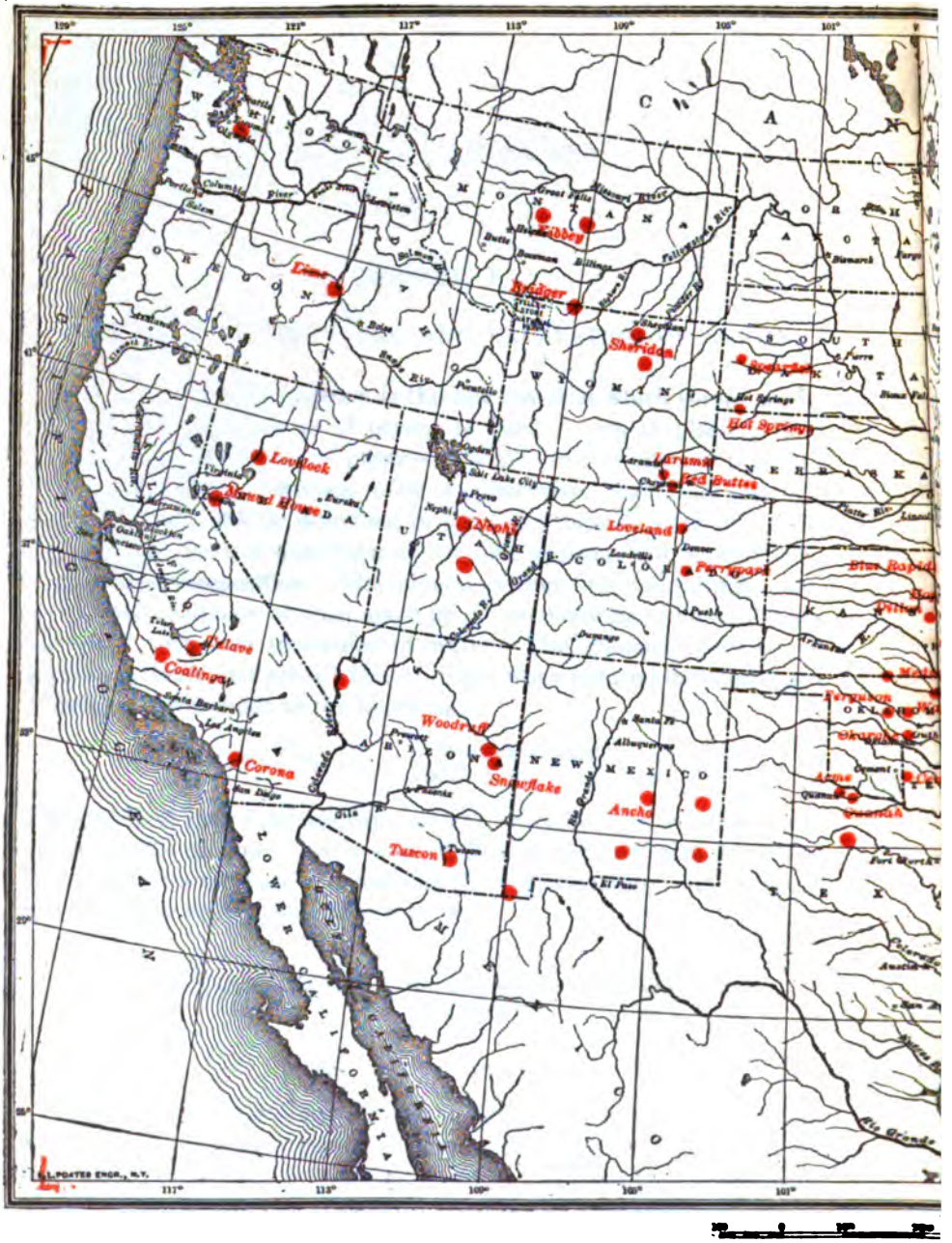
Chemical composition.—The mineral gypsum, when absolutely pure, is a hydrous sulphate of lime, made up of one molecule of lime sulphate combined with two molecules of water. The chemical formula of gypsum is therefore $CaSO_4+2H_2O$. This, when reduced to percentages of weight, corresponds to the following:

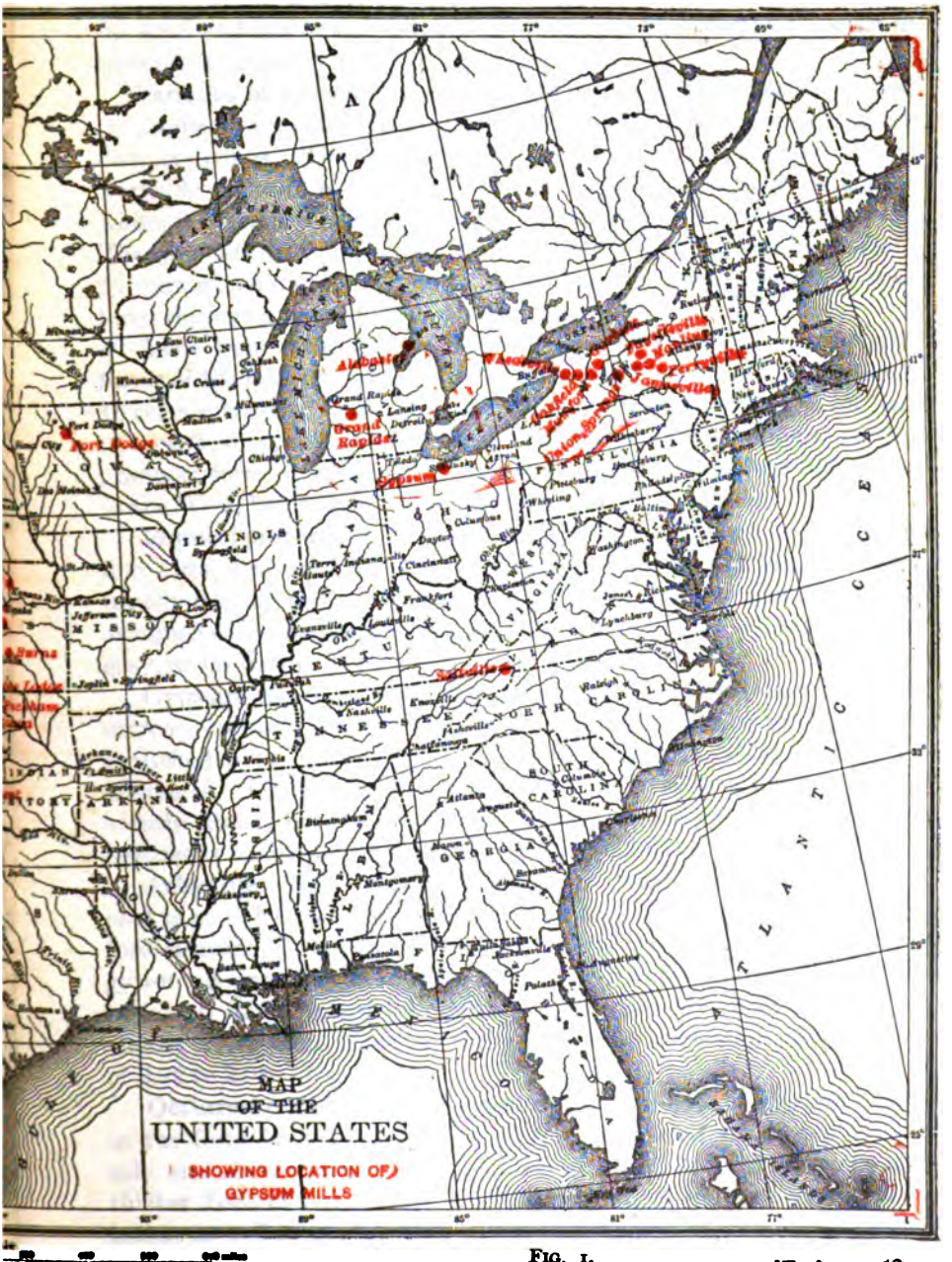
Gypsum ($CaSO_4+2H_2O$) =	Lime sulphate ($CaSO_4$)	79.1%
	Water (H_2O)	20.9

The 79.1% of lime sulphate can, in turn, be considered as being made up of 32.6% of lime (CaO), plus 46.5% of sulphur trioxide (SO_3). Reduced to its ultimate components, the composition of pure gypsum may therefore be represented as follows:

Gypsum ($CaSO_4+2H_2O$) =	Lime (CaO)	32.6%
	Sulphur trioxide (SO_3)	46.5
	Water (H_2O)	20.9
		100.0

Deposits of gypsum large enough to be worked for plaster are, however, rarely even approximately as pure as this. Gypsum as excavated for a plaster-plant will usually carry varying and often high percentages of such impurities as clay, limestone, magnesian limestone, iron oxide, etc. Table 8, on page 53, gives a number of analyses of the gypsum


Libby
Lima
Bridger
Sheridan
Hot Springs
Laramie
Red Buttes
Loyalton
Lovelock
Ogden
Nephi
Loveland
Fort Grant
Blue Rapids
Coalinga
Woodruff
Corona
Snowflake
Tucson
Ancho
Arms
Gulf of California
Lower California
El Paso
Rio Grande
Canada
Mexico
Colorado
Nebraska
Oklahoma
Texas
Utah
Nevada
Arizona
New Mexico
Wyoming
Montana
Oregon
Idaho
Pacific Ocean
Salt Lake City
Denver
Albuquerque
Santa Fe
Phoenix
Los Angeles
San Diego
Portland
Seattle
Spokane
Boise
Reno
Yuma
Pueblo
Amarillo
Fort Worth
Abilene
Wichita
Topeka
Omaha
Lincoln
Bismarck
Billings
Great Falls
Helena
Butte
Missoula
Kalispell
Lethbridge
Calgary
Edmonton
Regina
Winnipeg
Saskatoon
Prince Albert
Medicine Hat
Moose Jaw
Brandon
Fort William
Port Arthur
Sault Ste. Marie
Sudbury
Toronto
Ottawa
Montreal
Quebec
Halifax
Saint John
Fredericton
Charlottetown
Moncton
Sydney
Yarmouth
Kingston
Belleville
Peterborough
Oshawa
Hamilton
Brantford
Windsor
London
Stratford
Kitchener
Guelph
Barrie
Orillia
Muskoka
Parry Sound
North Bay
Timmins
Cochrane
Kapuskasing
Hearst
Geraldton
Longlac
Nipigon
Thunder Bay
Kenora
Dryden
Sioux Lookout
Red Lake
Pickle Lake
Fort Severn
Moosonee
Moose Factory
Cochrane
Kirkland Lake
Haileybury
New Liskeard
Temiskaming
Cobalt
Sturgeon Falls
Pembroke
Renfrew
Arnprior
Carleton Place
Almonte
Perth
Smiths Falls
Brockville
Prescott
Cornwall
Alexandria
Hawkesbury
Lachute
Saint Jerome
Joliette
Berthierville
Three Rivers
Shawinigan
Trois-Rivières
Drummondville
Sherbrooke
Magog
Granby
Saint Hyacinthe
Sorel
Saint Johns
Chambly
Valleyfield
Huntingdon
Saint Lambert
Longueuil
Laprairie
Beauharnois
Saint Timothée
Saint Lazare
Vaudreuil
Hudson
Oka
Saint Eustache
Saint Rose
Laval
Montreal
Verdun
Lachine
Saint Pierre
Dorval
Pointe Claire
Beaconsfield
Baie d'Urfé
Sainte Anne de Bellevue
Saint Anne de Bellevue
Saint Anne de Bellevue
Saint


MAP
OF THE
UNITED STATES
SHOWING LOCATION OF
GYPSUM MILLS
ATLANTIC OCEAN
Grand Rapids
Detroit
Cleveland
Buffalo
Pittsburg
Baltimore
Washington
Philadelphia
Richmond
Nashville
Knoxville
Charleston
Atlanta
Augusta
Savannah
Jacksonville
Montgomery
Mobile
Pensacola
Memphis
Vicksburg
Louisville
Cincinnati
Columbus
Springfield
Chicago
Milwaukee
Madison
Green Bay
Duluth
Minneapolis
St. Paul
Fort Dodge
Omaha
Kansas City
St. Louis
Indianapolis
Evansville
Terre Haute
Dayton
Toledo
Erie
Rochester
Albany
Syracuse
Scranton
Wheeling
Parkersburg
Lynchburg
Norfolk
Raleigh
Wilmington
Columbia
Greenville
Birmingham
Meridian
Jackson
Shreveport
Little Rock
Fort Smith
Joplin
Springfield
Jefferson City
Quincy
Peoria
Rockford
Milwaukee
Green Bay
Marquette
Houghton
Duluth
Minneapolis
Fargo
Sioux Falls
Yankton
Sioux City
Des Moines
Davenport
Cedar Rapids
Iowa City
Waterloo
Dubuque
Rock Island
Galesburg
Quincy
Hannibal
Springfield
Decatur
Terre Haute
Indianapolis
Richmond
Fort Wayne
Toledo
Sandusky
Akron
Youngstown
Erie
Buffalo
Rochester
Syracuse
Albany
Utica
Binghamton
Elmira
Scranton
Wilkesbarre
Allentown
Reading
Harrisburg
Pittsburg
Altoona
Johnstown
Wheeling
Parkersburg
Charleston
Huntington
Ashland
Lexington
Frankfort
Louisville
Owensboro
Evansville
Paducah
Cairo
Memphis
Nashville
Chattanooga
Knoxville
Asheville
Greensboro
Raleigh
Wilmington
Charleston
Columbia
Greenville
Spartanburg
Augusta
Savannah
Jacksonville
Tallahassee
Pensacola
Mobile
Montgomery
Birmingham
Gadsden
Anniston
Atlanta
Macon
Columbus
Meridian
Vicksburg
Jackson
Natchez
New Orleans
Baton Rouge
Lake Charles
Shreveport
Monroe
Texarkana
Little Rock
Pine Bluff
Fort Smith
Hot Springs
Joplin
Springfield
Jefferson City
St. Louis
Kansas City
Omaha
Lincoln
Grand Island
Hastings
Fremont
Norfolk

used at various plaster-plants; and a glance at this table will show the kind and amount of impurities which may be expected to occur in commercial gypsum.

Varieties of gypsum.—Owing to differences in form, texture, color, etc., gypsum presents several varieties, some of which have been given distinct names. The ordinary form in which gypsum occurs in the workable deposits is as *massive* or *rock gypsum*. *Alabaster* is a pure white, fine-grained massive gypsum, occasionally used for statuary, etc. The term *selenite* is applied to the crystalline, white, almost transparent gypsum which occurs frequently, but in relatively small quantity, scattered through a deposit of massive gypsum.

Aside from these various forms of rock gypsum, two less massive forms of the mineral are to be noted as being of commercial importance. In certain Western States and Territories deposits of *earthy gypsum*, *gypsum earth*, or *gypsite* occur. These deposits contain an impure, earthy, granular form of gypsum. Deposits of *gypsum sands* are also found in the West, being dunes or heaps of fine grains of gypsum.

Physical properties.—Pure gypsum is white and, when in the crystalline form, translucent. The impurities which it commonly contains usually destroy its translucency and affect its color, so that the mineral as mined is an opaque, fine-grained mass, varying from white to reddish, gray, or brown in color.

Gypsum can be distinguished from most other minerals by its extreme softness, for even when in the crystalline form it can be readily scratched by the finger-nail. When treated with acids it does not effervesce. On heating it loses its water of crystallization and, if previously translucent, becomes a chalky, opaque white. Pure crystalline specimens have a specific gravity * of 2.30 to 2.33.

Anhydrite.—The mineral *anhydrite* is closely related to gypsum, as it is an *anhydrous* lime sulphate, with the formula $CaSO_4$. It therefore corresponds in composition to the product obtained by heating gypsum so strongly as to drive off all of its water of combination (see pages 31, 32). Anhydrite occurs, but in relatively small amounts, in almost all gypsum deposits. Pure specimens have a specific gravity * of 2.92 to 2.98.

Occurrence and origin of gypsum deposits.—Rock gypsum occurs in the form of beds, frequently closely associated with beds of rock salt, and almost always interstratified with thin beds of limestone and thicker beds of red shales. Such gypsum beds may vary greatly in extent as well as in thickness. Beds now worked in different American

* Clarke, F. W. Constants of Nature, Part I, pp. 81, 82.

localities, for example, vary from six to sixty feet in thickness. The gypsum occurring in the beds frequently contains a considerable percentage of impurities, as is shown by the analyses given in Table 8, page 53.

Deposits of rock gypsum have been formed by the gradual evaporation, in lake basins or shallow arms of the sea, of waters carrying lime sulphate in solution. If any natural water be evaporated to a sufficient extent, it will deposit the salts which it contains, the order in which the various salts are deposited depending principally upon their relative proportions in the water and their solubility. A normal water, whether from stream, lake, or ocean, will carry as its three commonest constituents lime carbonate, lime sulphate, and sodium chloride. If such a water be evaporated, therefore, deposits of limestone, gypsum, and common salt would result: and, as above noted, these three minerals are very common associates in gypsum deposits.

Gypsum-earth deposits consist of masses of small crystals or grains of gypsum, intermingled usually with much clayey matter, sand, etc. Such deposits occur in depressions, and are supposed to be formed by the evaporation of spring-waters which have taken up lime sulphate in solution from underlying beds of rock gypsum, only to deposit it again on reaching the surface and being subjected to evaporation.

In certain areas in the West, notably in Arizona and New Mexico, deposits of gypsum sand occur. These deposits are made up of fine grains of gypsum, worn off from outcrops of rock gypsum and carried by the wind to the place of deposition.

Geologic distribution of gypsum deposits.—Gypsum has a very wide geological range, but the *workable* gypsum deposits of the United States occur at only a few geological horizons. The Salina group of the Silurian carries large gypsum deposits which are worked in New York, Ontario, Ohio, and Michigan. The Lower Carboniferous carries workable gypsum deposits in Virginia, Michigan, and Montana. Most of the deposits west of the Mississippi occur in rocks of Permian or somewhat later age. Three geological series, therefore, carry almost all of the workable gypsum of the United States.

Distribution of gypsum in the United States.—The gypsum-producing localities of the United States are indicated on the accompanying map This map is taken from the publication cited below,* to which the reader is referred for a much more detailed discussion of the subject, and from which most of the descriptive matter given below has been abstracted.

* "Gypsum Deposits of the United States," by George I. Adams and others. Bulletin No. 223, U. S. Geological Survey. Washington, D. C.

East of the Mississippi River, the producing localities are confined to central and western New York, southwestern Virginia, northern Ohio, and two widely separated areas in Michigan; while a large unworked deposit occurs in Florida. West of that river, gypsum deposits are both numerous and widely distributed, and plaster-mills are in operation in fourteen of the Western States and Territories.

Brief descriptions of the gypsum resources of the various States are given below, the States being taken up, for convenience of reference, in alphabetical order.

Arizona.—Gypsum can be obtained in quantity at several localities in southern Arizona, the following being particularly noteworthy; (1) In the Santa Rita Mts., Pima County, southeast of Tucson: (2) in the low hills along the course of San Pedro River, Cochise and Pinal counties; (3) in the Sierrita Mts., Pima County, south of Tucson; (4) in the foothills of the Santa Catalina Mts., Pima County, north of Tucson; (5) on the Fort Apache Reservation, Navajo County. Of these localities only the fourth, north of Tucson, has as yet been commercially developed.

California.—In the Tertiary rocks of California gypsum is widely distributed. It is found throughout nearly all the Coast Ranges, particularly south of San Francisco Bay, in the foothills of the Great Valley, and in the valleys of southern California. Deposits are known to occur in the counties of Fresno, Kings, Monterey, Kern, San Luis Obispo, Santa Barbara, Ventura, Los Angeles, San Bernardino, Riverside, and Orange.

Colorado.—The gypsum-producing localities of Colorado occur at intervals from the northern to the southern border of the State, along the eastern foothills of the Rocky Mountains. "Gypsum has been worked extensively near Loveland: beds have also been opened on Bear Creek, near Morrison, and eight miles to the southeast, on Deer Creek. Quarries have been developed near Perry Park and in the Garden of the Gods, near Colorado City, and also in the vicinity of Canyon City." Other deposits, as yet unworked, are known to occur in the central and western parts of the State.

Florida.—An extensive area of gypsum, 6 to 8 feet thick, has been described as occurring about six miles west of Panasoffkee, Fla., on a low-lying area of hummock-land known as Bear Island. The material has not, as yet, been exploited.

Iowa.—The gypsum of Iowa is confined to a single area of 60 to 70 square miles, near Fort Dodge, Webster County. The material occurs in one bed, which varies from 10 to 25 feet in thickness. It has been

extensively worked, eight plaster-mills being now in operation in the district.

Kansas.—"The gypsum of Kansas consists of extensive beds of rock gypsum and a number of deposits of secondary gypsum, or gypsite. Some of the rock gypsum is suited to the manufacture of the finer grades of plaster of Paris, and the gypsite is particularly adapted for wall and cement plasters. There is a sufficient quantity of the gypsite now known to permit extensive operations for a number of years. Certain of the deposits, however, have shown signs of exhaustion, and have been abandoned. It is probable that others will be discovered, as there is a demand for further development of the industry. The rock-gypsum beds are so vast in their proportions that only those which are favorably situated with respect to transportation facilities will probably be worked.

"The area in which gypsum is found is an irregular belt extending northeast and southwest across the State, as indicated on the accompanying map of Kansas (Fig. 2). It is naturally divided into three districts, which, from the important centers of manufacture, may be named the northern or Blue Rapids area, in Marshall County; the central or Gypsumcity area, in Dickinson and Saline counties; and the southern or Medicine Lodge area, in Barber and Comanche counties. A number of small areas have been developed between these, connecting more or less closely the three main areas. The gypsum is found at Manhattan and north of that city, though not worked. It is worked at Langford, in the southern part of Clay County, and is found near Manchester, in the northern part of Dickinson County. Gypsum is worked near Burns, and has in past years been worked near Peabody and Furley, and large deposits are known near Tampa. Farther south, in Sumner County, a large mill has been operated at Mulvane, and gypsum has been quarried at Geuda Springs. These different localities show an almost continuous belt of gypsum across the State."

Michigan.—Gypsum is at present worked in two distinct areas in Michigan, while a third locality may prove to be of importance in the future. The two producing areas are (1) in the vicinity of Grand Rapids; and (2) at Alabaster, near Saginaw Bay. The third, and as yet unexploited, area is near St. Ignace, on the Upper Peninsula.

Montana.—Gypsum is worked for plaster in Cascade and Carbon counties, and is known to occur at many other localities in the State.

Nevada.—At Moundhouse and Lovelocks, in northwestern Nevada, gypsum deposits have been developed. Large deposits also occur in southern Nevada.

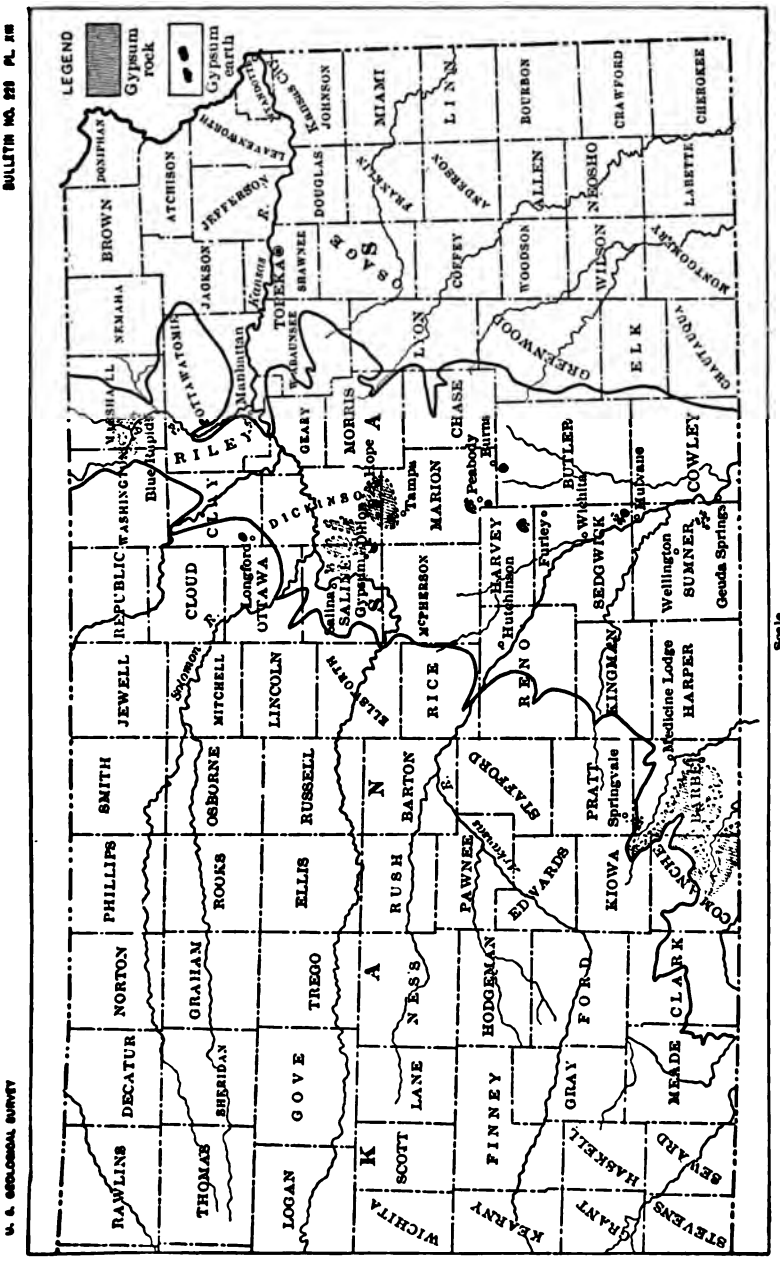


FIG. 2.—Map of Kansas, showing location of gypsum deposits.

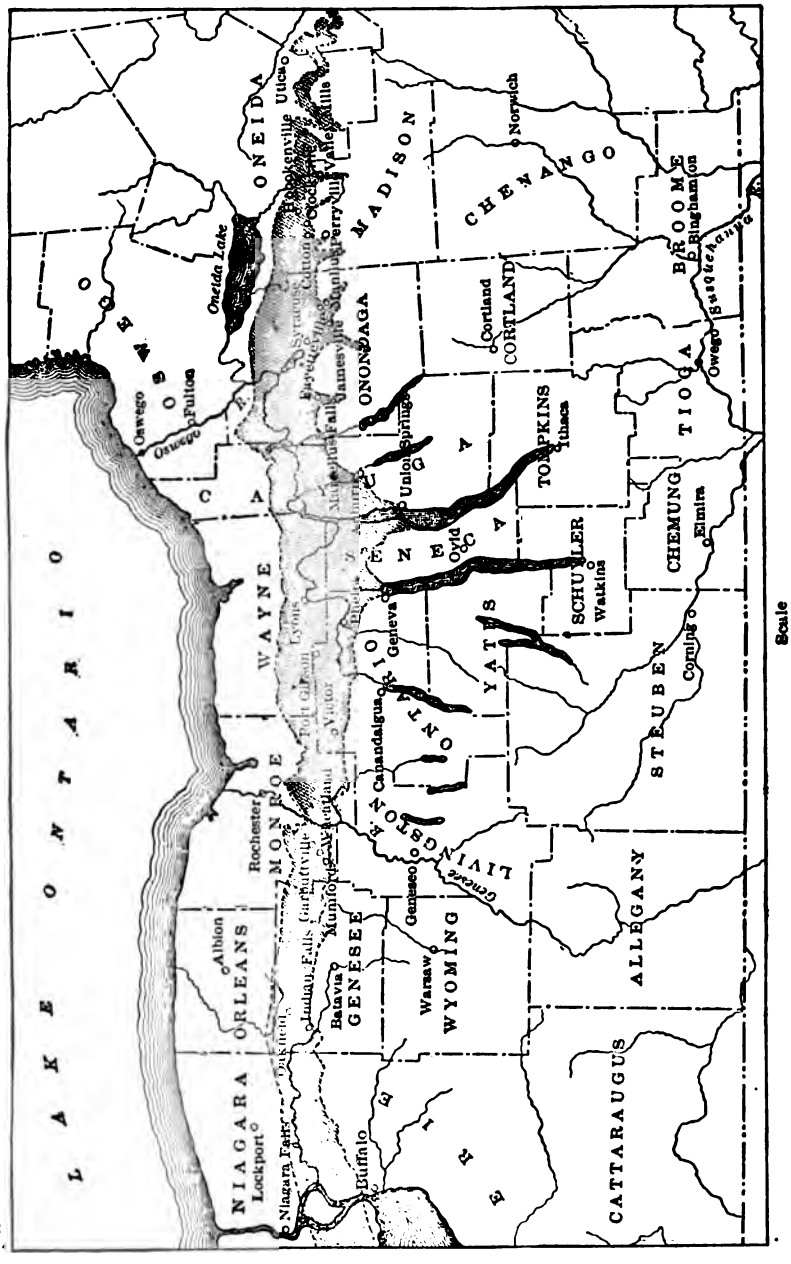


FIG. 3.—Map of New York, showing extent of gypsum-bearing formation.

New Mexico.—Though gypsum is known to occur in quantity at many points, the only commercial development has been at Ancho, where a plaster-mill is now in operation.

New York.—The gypsum in New York State occurs as rock gypsum interbedded with shales and shaly limestones. Several gypsum beds, separated by shales, usually occur in any given section. They are lenticular in shape, but of such horizontal extent that in any given quarry they are usually of practically uniform thickness. Those that are worked vary from 4 to 10 feet in thickness in most of the quarries, but at Fayetteville a 30-foot bed is exposed. The area in which the gypsum-bearing formations are found as shown in the map, Fig. 3, extends through the central part of the State, the productive portion of the belt including parts of Madison, Onondaga, Cayuga, Ontario, Genesee, Monroe, Livingston, and Erie counties.

The most easterly points at which gypsum has been worked are in Madison County, but the product there is small and is marketed locally for use as land-plaster. In Onondaga County, at Marcellus, Fayetteville, and other points, large quarries are operated, part of the product being calcined and part ground for land-plaster. The quarries near Union Springs, in Cayuga County, produce principally land-plaster, as do those of Phillipsport, Gibson, and Victor, in Ontario County. The gypsum from Mumford, Wheatland, Garbuttville, and Oakfield is used chiefly for calcined plaster.

Ohio.—"The gypsum deposits of Ohio which are of economic value consist of beds of rock gypsum occurring in the northwestern part of the State. They have been known since the first settlements were made on the northern shore of Sandusky Bay. The exposures lie at about the level of the waters of the bay, in some places rising a few feet above it. In addition to the deposits of economic importance, gypsum is found in small pockets and isolated bodies throughout the area of the Salina group, which occurs extensively in northwestern Ohio. The deposits which are worked vary considerably in thickness, ranging from a few inches up to 9 feet. On the north shore of Sandusky Bay, in Portage Township, Ottawa County, 1500 to 2000 acres of land have been thoroughly prospected with a core-drill, and it has been shown that there are from 150 to 200 acres of workable gypsum. On the south shore of the bay, about 2½ miles northwest of the town of Castalia, drilling has shown the presence of another area of workable gypsum, but no developments have yet been undertaken. The location of these deposits is shown on the accompanying map, Fig. 4. It is estimated that at the present rate

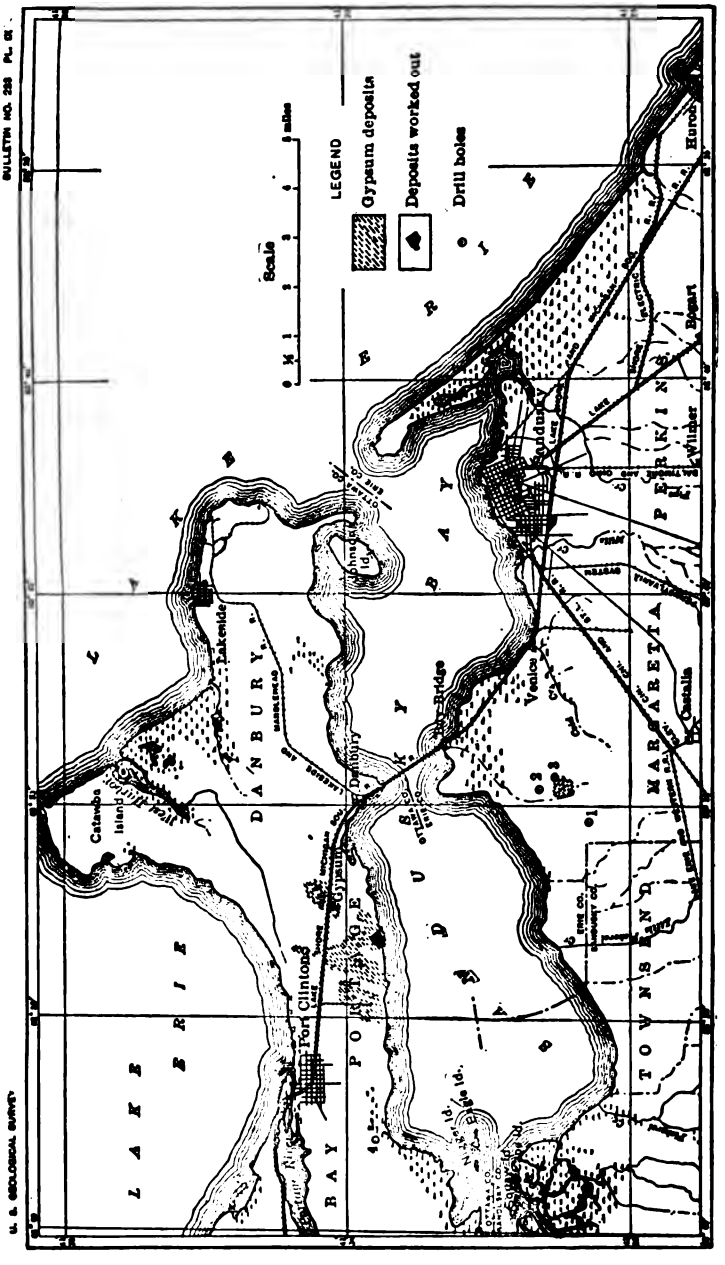


FIG. 4.—Map of the gypsum deposits of Ohio.

of production the known deposits will last about twenty-five years."

Oklahoma.—Oklahoma occupies a central position in the belt of country which carries extensive gypsum deposits all the way from the northern part of Kansas into central Texas (see Fig. 1). Within its borders the number and thickness of the beds appear to be greater than to the north and south. "The amount of gypsum appears to be inexhaustible. With perhaps two exceptions, each of the western counties contains enough material to supply the United States for an indefinite length of time, and there are in addition considerable deposits in the eastern part of the Territory." The gypsum in Oklahoma may be considered as occurring in four regions: (1) the Kay County region; (2) the main line of gypsum hills, extending from Canadian County northwest through Kingfisher, Blaine, Woods, and Woodward counties to the Kansas line; (3) the second gypsum hills, parallel with the main gypsum hills, and from 50 to 70 miles farther southwest, which extend from the Keechi Hills, in southeastern Caddo County, northwestward through Washita, Custer, Dewey, and Day counties; and (4) the Greer County region, occupying the greater part of western Greer County and the extreme southeastern corner of Roger Mills County.

The deposits in Kay County consist of earthy gyspum, or gypsite. In the other three regions rock gypsum predominates, although there are numerous localities where earthy gypsum occurs in workable bodies.

Oregon.—Gypsum occurs in Oregon in only one known and exploited locality. This is on the eastern border of the State, near the middle point of the boundary-line, on a ridge dividing Burnt River and Snake River. A plaster-plant located at Lime uses material from this locality.

South Dakota.—"In the Black Hills uplift there is brought to the surface an elliptical outcrop of the Red Beds surrounding the high ridges and plateaus of the central portion of the Black Hills. The area is about 100 miles long by 50 miles wide, and the outcrop zone has an average width of 3 miles, except in a few districts where the rocks dip steeply, where it is much narrower. The formation consists mainly of red sandy shales, with included beds of gypsum at various horizons, some of which are continuous for long distances, while others are of local occurrence. The thickness of the deposits varies greatly, but in some districts over 30 feet of pure white gypsum occur, and nearly throughout the outcrop of the formation it contains deposits of sufficient thickness and extent as to have commercial value.

"The gypsum is a prominent feature about Hot Springs. Here the principal beds occur about 60 feet above the base of the formation and

have a thickness of 33½ feet, exclusive of the 10-foot parting of shale between them, but this thickness diminishes somewhat northward and rapidly southward."

Texas.—"The largest area in Texas containing deposits of gypsum lies east of the foot of the Staked Plains, in northern Texas. The beds have an approximately northeast-southwest strike and extend from Red River to the Colorado in an irregular line, the sinuosities of which are produced by the valleys of the eastward-flowing streams. This belt is a continuation of the deposits in Oklahoma.

"In the eastern part of El Paso County, to the east of Guadaloupe Mountains, there is an area of gypsum which extends beyond the border of the State northward into New Mexico. It lies north of the Texas-Pacific Railroad and west of Pecos River. In a few localities this great plain of gypsum is overlain by beds of later limestone and conglomerate. The gypsum is conspicuously exposed along the course of Delaware Creek, a stream rising in the foothills of the Guadaloupe Mountains and flowing eastward into the Pecos.

"In the Malone Mountains in El Paso County there is a third area which contains notable deposits of rock gypsum. This locality has the advantage of being situated near the Southern Pacific Railway."

Utah.—"The more important known deposits occur in the central and southern portions of the State, in Juab County, east of Nephi; in Sampete and Sevier counties, near Salina; in Millard County, at White Mountain, near Fillmore, and in Wayne County in South Wash. They are all of the rock-gypsum type, except the one near Fillmore, which is in the secondary form of unconsolidated crystalline and granular gypsum blown up from dry lakes into dunes. Deposits are also known in Emery County, about forty miles southeast of Richfield; in Kane County, near Kanab; in Grand County, between Grand River and the La Sal Mountains; in Sanpete County, near Gunnison; in the eastern part of Washington County (?), between Duck Lake and Rockville, and at other places. Recently enormous deposits of gypsum have been reported from Iron County, at points so far from lines of transportation, however, as to render their exploitation impracticable for the present."

Virginia.—All the workable gypsum deposits of Virginia occur in Washington and Smyth counties, in the valley of the North Fork of Holston River. The area within which the known deposits are located is a narrow belt about sixteen miles in length, extending from a short distance southwest of Saltville to a point about three miles west of Chatham Hill post-office.

The material occurs as rock gypsum, interbedded with shales and shaly limestones of Carboniferous age. The beds of gypsum average 30 feet in thickness at the localities at which they are now worked. The rocks of the district dip at a high angle, however, usually between 25° and 45°, so that certain wells which have been drilled are in the gypsum for long distances, and accordingly immense thicknesses of gypsum have been erroneously reported, because the inclination of the deposits was not taken into account. Near Saltville the dip of the gypsum beds which are worked is toward the northwest; at the mines further up the valley the dip is to the southeast.

The development of the gypsum industry in this area has been governed almost entirely by the transportation facilities. The deposits in the upper valley, though extensive and easily workable, have not been largely exploited, owing to the long wagon-haul necessary. The deposits at Saltville and Plasterco, which are on a branch of the Norfolk and Western Railroad, have furnished the principal output.

Throughout the entire area the dip of the gypsum beds is so high as to require mining, except at the commencement of the working.

Wyoming.—Though gypsum deposits occur at many localities in the State, only two plaster-plants are at present in operation. These are located at Laramie and Red Buttes respectively. A considerable extension of the Wyoming plaster industry may, however, be expected; for the supplies of gypsum are large and accessible.

Canada.—Gypsum occurs in New Brunswick, associated with Lower Carboniferous limestones, particularly large deposits being shown near Hillsboro, Albert County. An analysis of a typical sample from Hillsboro is given as No. 25, of Table 9, page 60.

The gypsum deposits of Ontario occur in the form of beds, associated with shales and limestones, in the Salina group. The principal exploited deposits are located along the valley of Grand River, from Paris in Brant County to near Cayuga in Haldimand County.

Extensive gypsum beds also occur in Devonian limestones along the Moose and French rivers, near James Bay: but these deposits are as yet entirely undeveloped.

In Nova Scotia thick beds of gypsum occur near St. John Harbor, Port Bevis, and Baddeck Bay, associated with Carboniferous limestones. An analysis of gypsum from near Baddeck Bay is given as No. 26 of Table 9, page 60.

Of the Canadian gypsum deposits, those of New Brunswick and Nova Scotia are of interest to American producers, for they have supplied large quantities of crude gypsum to plaster plants located in the

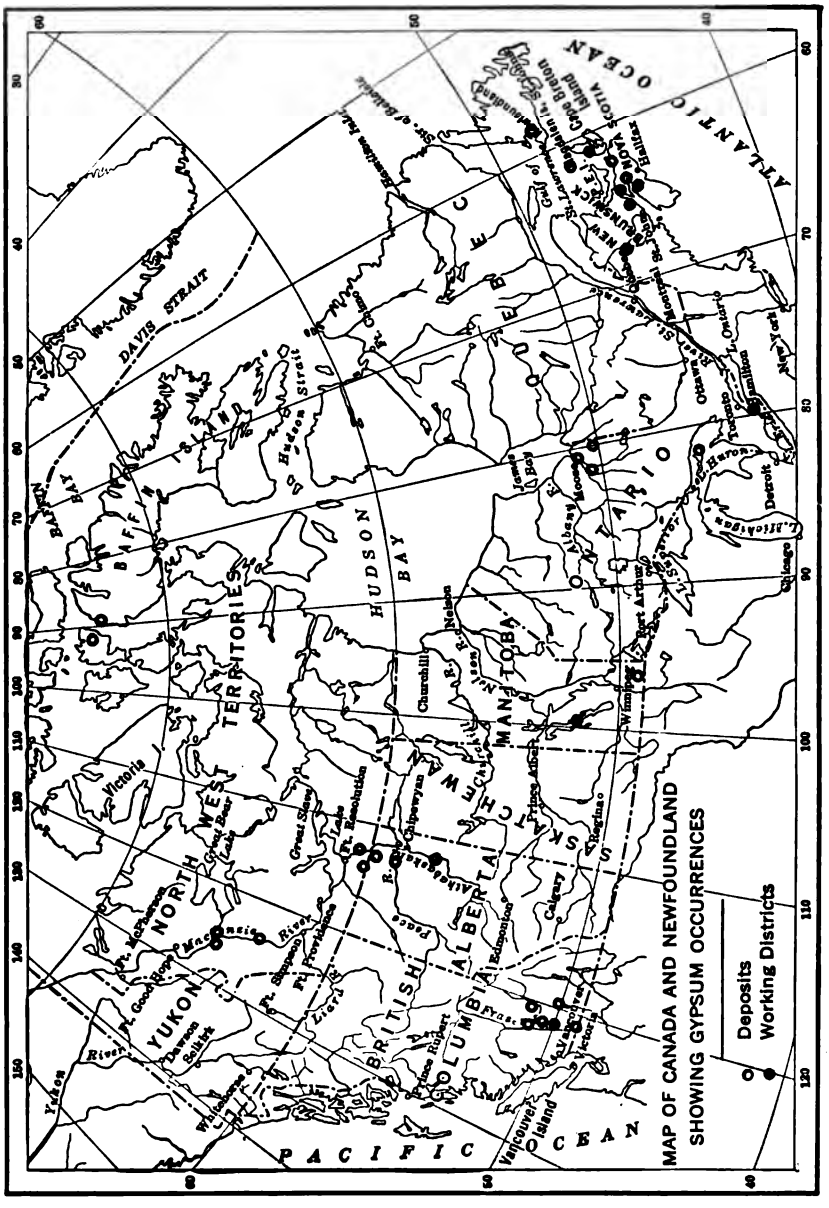


FIG. 5.—Map of Canada and Newfoundland, Showing Gypsum Deposits.
Canadian Data from Map by Canada Mines Dept. Newfoundland Data from Notes by E. C. Eckel.

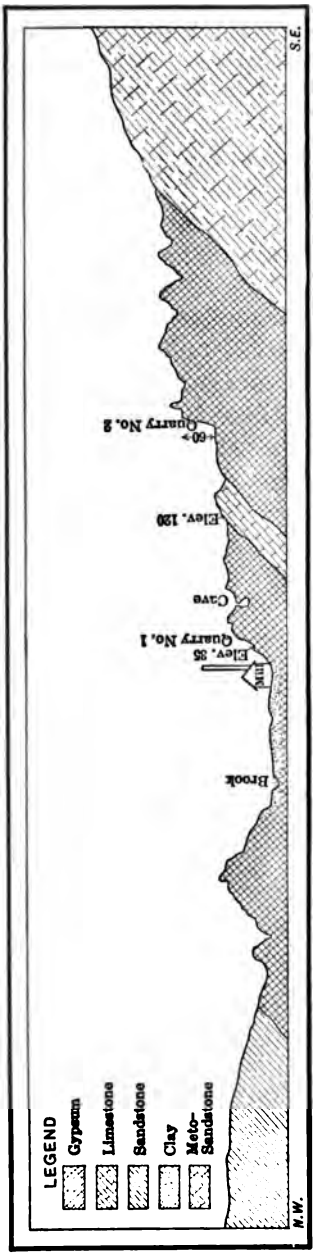


FIG. 6.—Cross section of gypsum deposits at Cheticamp, Nova Scotia. (After Jennison).

United States. Most of this gypsum from the Maritime Provinces is used in plants located in the seaboard cities, but a considerable amount of it is calcined as far west as Syracuse, N. Y. Further details on this matter will be found in Chapter V.

In the prairie and mountain provinces, from Manitoba to the Pacific, gypsum deposits often of great size are known to occur. These are in newer geological formations than those of Ontario and Nova Scotia, for the gypsums of western Canada are mostly in Triassic and Tertiary rocks, like the corresponding deposits of the western United States.

Manitoba contains gypsum deposits of both older and newer series. In the region between Lakes Manitoba and Winnipeg, for example, Lower Silurian gypsum deposits occur extensively, and have been developed for plaster manufacture. In southern Manitoba, on the other hand, beds of much later age have been prospected.

Alberta is known to contain gypsum deposits at a number of localities in the northern port of the province, along the Athabasca and Peace River drainages. Their location, distant from both transportation and markets at present, renders these deposits of little economic importance now.

In British Columbia gypsum has been found and worked at Merritt, in the Nicola Valley; and its occurrence has been reported from a number of other points in the province.

For details concerning the Canadian deposits reference should be made to the two reports following, of which that of Cole is of course the more general and important:

Cole, L. H. Gypsum in Canada; its occurrence, exploitation and technology. Bulletin 245, Mines Branch, Canadian Dept. of Mines, Ottawa, 1913, 256 pp., maps.

Jennison, W. F. Gypsum deposits of the Maritime Provinces. Bulletin 84, Mines Branch, Canadian Dept. Mines, Ottawa, 1911, 171 pp., maps.

Newfoundland.—Extensive deposits of gypsum occur in the Lower Carboniferous rocks of western Newfoundland. These are specially well shown on and near the southern portion of the west coast of the island. Though these deposits are essentially continuous for many miles, transportation requirements will for the present limit attention to those which are located on the west coast or near the railroad. Of these three coast areas are notable; the southernmost in the Codroy Island—Cape Anguille region; the second, at Plaster Cove, in the so-called Highland region; and the third at Romaines Brook. In addition the deposits along Fishels Brook on the railroad are important.

Examination of gypsum deposits.—In examining and testing a gypsum deposit, it is safe to assume that the gypsum is of sedimentary origin, and that it occurs in more or less regular beds or lenses. The chief problems are concerned with determining the average composition of the rock, the presence and proportion of anhydrite, the thickness of the stripping, and the average thickness of the gypsum bed itself.

In default of actual excavation, the best implement for determining most of the factors of value noted above is the earth auger, for commonly the material overlying the gypsum, near the outcrop at least, will be soil or soft clay, and in such material the auger gives economical and fairly accurate results. An auger can be worked in the gypsum itself, though with difficulty increasing rapidly with the depth from the surface. In most cases the best practice will be to use the auger to determine the thickness of overburden, driving it down until it cuts sufficiently into the gypsum to prove that a solid bed has been reached.

When the gypsum is covered by beds of harder rock, such as shales or limestones, the auger is of course useless for exploration. In such cases churn drilling or rotary drills must be employed to determine the thicknesses of the gypsum beds and to secure the samples for analysis.

A theoretically pure gypsum carries nothing but lime sulphate and combined water; and some of the crystalline forms of gypsum often approximate this condition of theoretical purity. In general, however, a deposit of gypsum large enough to be of commercial use will show that certain impurities are present to a greater or lesser extent, throughout the mass of the deposit.

In most beds of rock gypsum such impurities will not ordinarily amount to more than 1 to 3 per cent of the total; and they will consist chiefly of lime carbonate, silica, alumina, iron oxide and magnesium carbonate. The analyses given in Table 9 on page 60 will serve to indicate the composition of rock gypsum actually used at many different and widely separated plants.

The gypsite or gypsum earth deposits are, in general, much more impure than those of rock gypsum; and as shown in Table 10, page 61, gypsite as mined may carry from 5 to 10 per cent or more of waste matter.

Excavation and handling of rock gypsum.—Deposits of rock gypsum are worked either in open quarries or in mines, the choice depending on the thickness of the bed, its dip, and the amount of stripping necessary. Usually work is commenced in an open cut on the outcrop of the gypsum bed. After the entire available face on the property has been opened in this manner, it is necessary to decide whether the work-

ings can be most economically driven as underground tunnels or slopes, or by stripping and open-cut work. At the Severance quarries at Fayetteville, N. Y., over 40 feet of shale and limestone stripping is removed, but the total thickness of gypsum beds shown here is 60 feet; and such heavy stripping could not be justified in order to work thinner beds.

Under ordinary conditions the cost of quarrying gypsum may range from 20 to 35 cents per ton, as compared with 40 to 60 cents per ton for mining it. In mining, large pillars must be left at frequent intervals, and timbering is necessary, in addition, for extensive workings.

Mining methods.—The mining methods practiced at a typical Kansas locality are described * as follows by Crane:

" As a rule, there is little or no system employed in laying out the workings. Main lines of haulage are run as continuations of the surface drifts, other openings being run parallel with them on further development, or run from the foot of a shaft sunk to the workable deposit. On one or both sides of the haulageways rooms are driven, which often run together, thus leaving odd and very irregularly shaped pillars. Long working-faces are often formed, which must be again broken by passages forming pillars for the support of the roof. Usually, however, single rooms, more or less irregular in shape, are opened up and worked until the handling of the product becomes inconvenient, when new and more advantageously placed openings are begun.

" The mine in question was opened by an adit, which, beginning on a fairly steep hillside, at a point on a level with the second floor of the mill, extends into the hill for a distance of about 1000 feet. No special attempt was made to align the adit, consequently considerable useless work was done. For the first 400 feet the adit runs approximately north; the next 300 feet shows a marked variation from the north-and-south line. An attempt was then made to rectify the deviation by driving a right-angled offset 25 feet in length; the remaining 300 feet was driven approximately parallel with the first 400 feet.

" Unfortunately, the adit was driven so nearly level as to render drainage very difficult, and much water stands in depressions on the limestone floor.

" The adit is lined with rough-hewn oak, walnut, and red-elm timber, except the last 300 feet, which has round timbers of similar material. Three-quarter sets—that is, sets with posts and caps only—are employed. The posts and caps are 6 feet 2 inches and 6 feet 4 inches

* Crane, W. R. The gypsum-plaster industry of Kansas. Eng. and Mining Journal, p. 442, March 17, 1904.

long, respectively, both being 8×8 inches in section. They are spaced 36 inches. The posts stand on a limestone stratum 2 feet in thickness, and therefore require no sills. The sets for the first 700 feet are lagged with 2×12-inch oak plank; the remaining 300 feet has plank lagging on the caps and pole-lagging on the posts. A single track of 36-inch gauge is laid in the middle of the tunnel for the mine-cars, which are drawn by mule-power. The cars have a capacity of from 800 to 1000 lbs. gypsum.

"The gypsum mined is 8.5 feet thick and is won by shooting it from the face or sides of the rooms, holes being bored by hand-operated post-augers, Hardscop make. The holes are 1.5 inches in diameter and range from 3 to 6 feet deep. Black powder of C grade is usually employed, the charge ranging from 6 to 14 inches per hole. Squibs are employed in firing the charges. The cost of explosive per ton of gypsum extracted is about four cents.

A 4×6-foot air-shaft connects the end of the adit with the surface, 96 feet above."

Working gypsum-earth deposits.—Deposits of gypsite or gypsum earth, being purely surface deposits of a soft granular material, can be worked best by methods entirely different from those used in excavating rock gypsum. The gypsum earth is not only soft, but frequently carries a large percentage of moisture: and as it freezes deeply because of this moisture, the Kansas deposits can be worked only during warm weather. If the gypsum earth is covered by soil or sand, this is stripped. The gypsum earth is then loosened by disk harrows or plows, and taken up by wheeled scrapers. It is then taken to drying-sheds, in order to get rid inexpensively of as much of the water as possible. The cost of working a gypsum-earth deposit, under average conditions, may fall between 10 and 25 cents per ton.

CHAPTER II.

CHEMISTRY OF GYPSUM-BURNING. MANUFACTURE OF PLASTERS.

BEFORE taking up the actual methods and details of plaster-manufacture, it will be of advantage to discuss briefly the chemical and physical principles on which the industry is based.

Chemistry of gypsum-burning.—Pure crude gypsum is a hydrous sulphate of lime, with a chemical formula $CaSO_4+2H_2O$. This corresponds to the composition:

$CaSO_4+2H_2O=$	Lime sulphate ($CaSO_4$)	Lime (CaO)	32.6%	=79.1%
		Sulphur trioxide (SO_3)	46.5	
	Water (H_2O)		20.9	
			100.0	

If pure crude gypsum be heated to a temperature of more than 212° F. and less than 400° F., a certain definite portion of the water of combination will be driven off, and the gypsum thus partially dehydrated will be plaster of Paris. Plaster of Paris has the formula $CaSO_4+\frac{1}{2}H_2O$, corresponding to the composition:

$CaSO_4+H_2O=$	Lime sulphate ($CaSO_4$)	93.8%
	Water (H_2O)	6.2

Three-fourths of the original water of combination have therefore been driven off in the course of the process. Dehydration to this extent can, as above noted, be accomplished at any temperature between 212° F. and 400° F. In actual practice, however, it is found most economical of fuel and time to carry on the process at the highest allowable temperatures; and 330° to 395° F. may be regarded as the usual limiting temperatures for plaster-manufacture.

About 400° F. is a critical temperature, for if gypsum be heated at temperatures much above this, it loses *all* of its water of combination, becoming an entirely anhydrous sulphate of lime, and useless as a normal plaster. Under certain conditions, however, gypsum burned at temperatures above 400° F. gains valuable properties. Such highly

burned gypsum products will be considered in Chapter IV, under the head of Flooring and Hard-finish Plasters.

Recurring to plasters burned at temperatures lower than 400° F., it may be said that if the gypsum is pure, the resulting plaster will harden or set very rapidly when mixed with water, reabsorbing sufficient water to regain its original composition of $CaSO_4+2H_2O$. Such quick-setting pure plasters are conveniently grouped as plaster of Paris. If, however, the crude gypsum carried a large percentage of impurities, or if certain materials are added to the plaster after burning, the product will set much more slowly. Such slow-setting plasters are of value in structural work, and are marketed under the somewhat misleading name of "cement plasters." The term is unfortunate, because such "cement plasters" are in no way related to the much better known "hydraulic cements" discussed later in this volume.

Using the properties above noted as a basis for classification, the group of plasters may be subdivided as follows:

CLASSIFICATION OF PLASTERS.

A. Produced by the incomplete dehydration of gypsum, the calcination being carried on at a temperature not exceeding 400° F.
   1. Produced by the calcination of a pure gypsum, no foreign materials being added either during or after calcination.....PLASTER OF PARIS.
   2. Produced by the calcination of a gypsum containing certain natural impurities, or by the addition to a calcined pure gypsum of certain materials which serve to retard the set of the product. CEMENT PLASTER.

B. Produced by the complete dehydration of gypsum, the calcination being carried on at temperatures exceeding 400° F.
   3. Produced by the calcination of a pure gypsum.....FLOORING-PLASTER
   4. Produced by the calcination, at a red heat or over, of gypsum to which certain substances (usually alum or borax) have been added.....HARD-FINISH PLASTER.

Commercial classification of plasters.—In the trade the names above suggested are used quite extensively, but at times in a careless and indefinite fashion.

Calcined plaster commonly means a burned plaster to which no retarder has been added. If the gypsum from which it was made was pure, the resulting *calcined plaster* will be a *plaster of Paris*, as defined above. If the gypsum used was impure, however, the resulting *calcined plaster* would be a *cement plaster*, as defined above.

Stucco is almost a synonym for *plaster of Paris*, as it contains no retarder and is made from fairly pure gypsum: but the product handled

commercially as *plaster of Paris* is usually more finely ground than *stucco* and is as white as possible.

Wall-plasters are made by adding not only retarder but also hair (or some other fiber) to *calcined plaster*.

Keene's "cement," Parian "cement," etc., are plasters used as hard finishes in buildings. Their properties are due to certain peculiarities of their manufacture, for which reference should be made to Chapter IV.

In the present chapter the manufacture of plaster of Paris, cement plaster, and wall-plaster will be taken up, and followed by a chapter on the properties of the resulting products. The manufacture and properties of the flooring and hard-finish plasters will be discussed together in Chapter IV.

Manufacture of Plaster of Paris, "Cement Plaster," and Wall-plaster.

Though plaster of Paris and "cement plasters" are very distinct so far as properties and fields of use are concerned, their processes of manufacture are so similar that they will be treated together in this chapter. It will be recalled that in manufacturing plaster of Paris a pure gypsum is used, so that the product sets very rapidly, while in making cement plasters slowness of set is obtained either by using a naturally impure gypsum or by adding a retarder to the material during or after its manufacture. Aside from this difference, and a slight difference in the calcining temperature, which is usually somewhat lower for plaster of Paris than for cement plaster, the methods employed in making the two products are closely similar.

Two operations are necessary in manufacturing both kinds of plaster: the raw material must be properly calcined and finely ground. The grinding may either precede or follow the burning, for the order of the two operations depends largely upon what calcining process is used. If the burning is carried on in kettles, the grinding is usually done first; but if the burning is carried on in ovens or rotating cylinders, the raw material is necessarily or advisably fed in lumps, and the fine grinding, therefore, follows the burning. In the present chapter the subject will be discussed under the following headings:

(1) Grinding gypsum and plaster.
(2) Calcining by the oven process.
(3) Calcining by the kettle process.
(4) Calcining by the rotary cylinder process.
(5) Addition of retarders and acceleration.
(6) Costs of plaster-manufacture.

Effect of temperature and time on properties.—Leduc and Chenu* have carried out important experiments to determine the effect which the temperature and duration of the burning have upon the properties of the resultant plasters. Some of the tests are presented here, arranged so as best to bring out the results.

TABLE 4.

EFFECT OF TEMPERATURE AND TIME ON PLASTER-BURNING.

Temperature of Burning, Centigrade.	Duration of Burning, Minutes.	Tests of Resulting Plasters.			
		Setting Time.		Compressive Strength, Kilograms per Square Centimeter.	
		Beginning, Minutes.	End, Minutes.	1 Day.	1 Week.
150 degrees	5	45	60	21.4	22.0
	30	40	95	18.2	18.0
	60	45	70	37.1	33.0
	120	45	75	27.3	31.0
200 degrees	5	27	62	34.3	33
	30	20	60	59	54
	60	25	45	67	56
	120	22	42	58	52
	240	15	35	78.7	91
250 degrees	5	13	33	76	72
	30	10	26	92	90
	60	7	27	86	90
	120	6	13	97	101
	240	4	16	87	88
300 degrees	5	4	18	80	101
	30	4	12	72	110
	60	2½	8½	65	91
	120	2	9	46	97
	240	1½	4½	50	100

These French experiments indicate that:

1. At whatever temperature the burning is conducted, within the limits of 150 and 300 degrees Centigrade, the initial and final sets are hastened by long burning.

2. The compressive strength shows a tendency to increase with length of burning time, at any temperature up to and including 250 degrees. Above this temperature the effect of longer exposure is injurious.

3. Time of burning being equal, the initial and final sets are hastened

* Leduc et Chenu. Chaux, Ciments, Platres, pp. 172–173.

by increased temperature up to the point of 300 degrees Centigrade. Above this, as will be seen later, they slow down markedly.

4. Time of burning being equal, the compressive strength tested at twenty-four hours increases with increase of temperature, up to 250 degrees. Above this it tends to fall off somewhat; and above 300 it falls off sharply.

5. Time of burning being equal, the compressive strength tested at one week tends to increase with temperature up to 300 degrees. Above that it also falls off, but more slowly than do the twenty-four-hour tests.

To a certain extent, therefore, time and temperature have equivalent effects upon the properties of the product, with the qualification that while overtime merely is of negative value, over-temperature may reach to the point of positive harm.

Finally, there is to be considered the effect of fine grinding of the crude gypsum. This, as might have been expected, aids materially in bringing about complete burning in much shorter time than when coarse gypsum is used.

Kind of fuel used.—Coal is used as fuel at most American plaster mills, though in a number of states west of the Mississippi oil is in use. The exact situation as regards fuel used at different plants is shown in the figures in the following table, made up from data given in reports of the United States Geological Survey.

TABLE 5.

FUELS USED AT AMERICAN PLASTER MILLS.

Kind of Fuel Used.	Number of Mills Using.			
	1910.	1911.	1912.	1913.
Coal	55	55	50	43
Oil	13	16	16	17
Wood	2	1	1	1
Coal and wood	..	1	1	
Coal and oil	..	..	1	2
Total number of mills reporting.	70	73	69	63

Grinding gypsum and plaster.—In American plants using the kettle-calcining process the gypsum is finely pulverized *before* calcination. This pulverizing is usually accomplished in three stages, though when gypsum earth is used instead of rock gypsum the coarse crushers are dispensed with. The three stages are:

(1) The lump gypsum, as quarried, is crushed to 2- to 4-inch size in a Blake, Gates, or other coarse crusher.

(2) The product of the coarse crushers is fed to reducers of the coffee-mill type, which crush it to about $\frac{1}{4}$ inch or so.

(3) The final pulverizing is accomplished in either buhrstone mills, Sturtevant rock-emery mills, or Stedman disintegrators. These reduce the gypsum so that from 55 to 65 per cent will pass a 100-mesh sieve, and it is then ready to be fed to the kettles.

FIG. 7.—Nipper for coarse crushing of gypsum. (Butterworth & Lowe.)

A typical series of gypsum-grinding machinery is shown in Figs. 7–9. Fig. 7 shows a "nipper," used for the first coarse reduction. It is a heavy crusher of the jaw type, and when used for gypsum-crushing is usually equipped with corrugated jaws, in order to prevent clogging. The machine shown in the illustration has a jaw-opening of $16\frac{1}{2}'' \times 25\frac{3}{4}''$, and a shipping-weight of 10,200 lbs. A smaller nipper, weighing 8100 lbs. and with a $36'' \times 12''$ belt pulley, is quoted as having a capacity of 10 to 14 tons per hour.

The "nipper" is usually followed by the "cracker" (Fig. 8), which is a heavy machine of the familiar toothed spindle type.

A cracker weighing 8000 lbs. has a capacity of 12 to 15 tons per hour.

For the final reduction the Stedman disintegrator, Sturtevant rock-emery mill, or ordinary buhrstones are generally used. The last two

FIG. 8.—Cracker for intermediate reduction. (Butterworth & Lowe.)

machines are described in a later section of this volume (pp. 234, 236), as they are quite extensively used in grinding natural-cement clinker.

The Stedman disintegrator (Fig. 9), is composed essentially of four concentrically placed cages, formed of steel bars. Of these cages, the first and third revolve in one direction, the second and fourth in the opposite. The material to be crushed is fed into a hopper which dis-

charges it at the center of the cages. The gypsum lumps are struck by the bars of the inner cage, and thrown outward at high velocity. The bars of the second cage, revolving in the opposite direction, strike

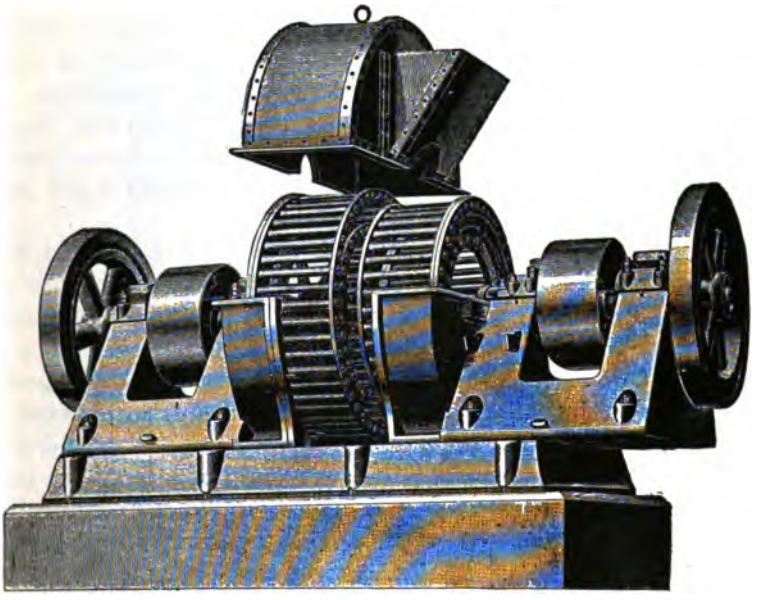


FIG. 9.—Stedman disintegrator, 50-inch, heavy pattern; open and slid apart.

them with a blow of double force, and this operation is repeated by the bars of the third and fourth cages in succession.

TABLE 6.

SIZES, CAPACITY, ETC., OF STEDMAN DISINTEGRATORS.

Size.	Horse-power.	Capacity in 10 Hours.	Weight, Lbs.
30-inch disintegrator, heavy pattern.....	6–9	8 to 10 tons	3,000
36- " " " "	12–18	18 " 25 "	5,500
42- " " light "	12–18	20 " 30 "	6,000
40- " " heavy "	20–25	25 " 35 "	10,000
44- " " " "	30–35	40 " 50 "	12,000
50- " " " "	35–45	60 " 75 "	15,000

After being reduced as above described, the gypsum is calcined. Usually it is necessary to regrind some of the product which comes from the kettles; and this may be accomplished in any of the fine grinders above noted.

When the rotary process is used, it is customary not to pulverize the material until *after* calcining. As calcined plaster is much easier to grind than crude gypsum, a considerable saving in power and repairs is effected by this difference in practice.

Calcining in ovens.—In the manufacture of the higher grades of plaster of Paris it is necessary that the material should be calcined with extreme uniformity and at exactly the proper temperature. This uniformity in burning is attainable in ovens, though the process is necessarily expensive in fuel and labor For these reasons the oven process has not been used in the United States, though it still persists in Europe for certain grades of plasters.

Calcining in kettles.—The favorite process in the United States, particularly in the plaster-plants of the Middle West, is that in which the calcination is effected in kettles. As noted later in discussing continuous calcining processes (pp. 50–54) the kettle process is slow, low in output, and expensive in fuel. For these reasons it will probably disappear as the continuous rotary calciner becomes perfected; but at present it is still used in the majority of American plaster-plants. The statements above should not be construed as a too sweeping condemnation of the kettle process, for that process is undoubtedly far superior in economy to its European progenitor, the oven process.

The following description of the process of calcining plaster in kettles is abstracted, in large part, from an admirable paper * by Wilkinson.

In this process the gypsum is ground, and charged into cylindrical "kettles." Heat is applied both at the bottom of the kettle and by flues passing entirely through the cylinder.

A heavy stone or brick masonry support is built for the kettle, inclosing a fire-space in the form of an inverted cone about 4 feet high. At the top of this cone a cast-iron flanged ring is set in the masonry. On this flange is placed the "kettle-bottom," which is an iron casting, concavo-convex in shape, a little less than 8 or 10 feet in diameter, with the convexity placed upward, the rise being 1 foot. This bottom has a thickness of $\frac{3}{4}$ inch at the edges and 4 inches at the crown. Kettle-bottoms must be made of the best scrap-iron, as ordinary scrap-iron does not last as long as pig. Sheet steel has been tried, but does not serve as well as the best scrap. "The life of a kettle-bottom is terminated by cracking. The cracks can be calked with asbestos cement, but the expense of stoppage and repairing soon overcomes the saving."

Within the past few years sectional kettle-bottoms have been introduced quite extensively. A kettle of this type is shown in Fig. 12,

* Trans. Am. Inst. Mining Engineers, vol. 27, pp. 514 et seq.

in which the kettle-bottom is composed of a central circular section and six other sections fitting around it. These sections are made of cast iron. The principal merit of this design is that in case any section

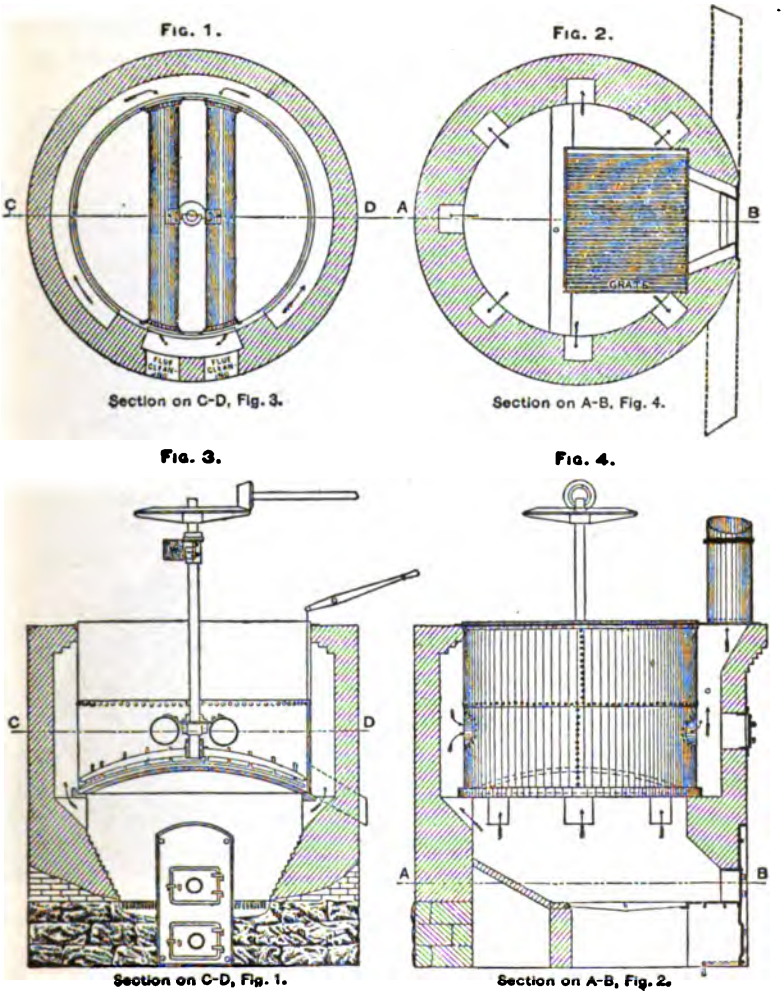


Fig. 10.—Construction and setting of gypsum-kettles.
(Trans. Am. Inst. Min. Engrs.)

of the kettle-bottom burns out, it can be replaced without disturbing the kettle or brickwork.

The kettle, which is placed on the kettle-bottom, is of boiler iron

$\frac{3}{8}$ to $\frac{5}{8}$ inch thick, and is commonly 8 to 10 feet in diameter and 6 to 8 feet deep. Such a kettle holds about 7 to 12 tons of raw material, producing from $5\frac{1}{2}$ to 10 tons of plaster. The kettle has two or four flues 12 inches in diameter, placed horizontally about 8 inches above the crown of the kettle-bottom and separated externally about 6 inches. After the kettle has been set, brick masonry is erected around it, gradu-

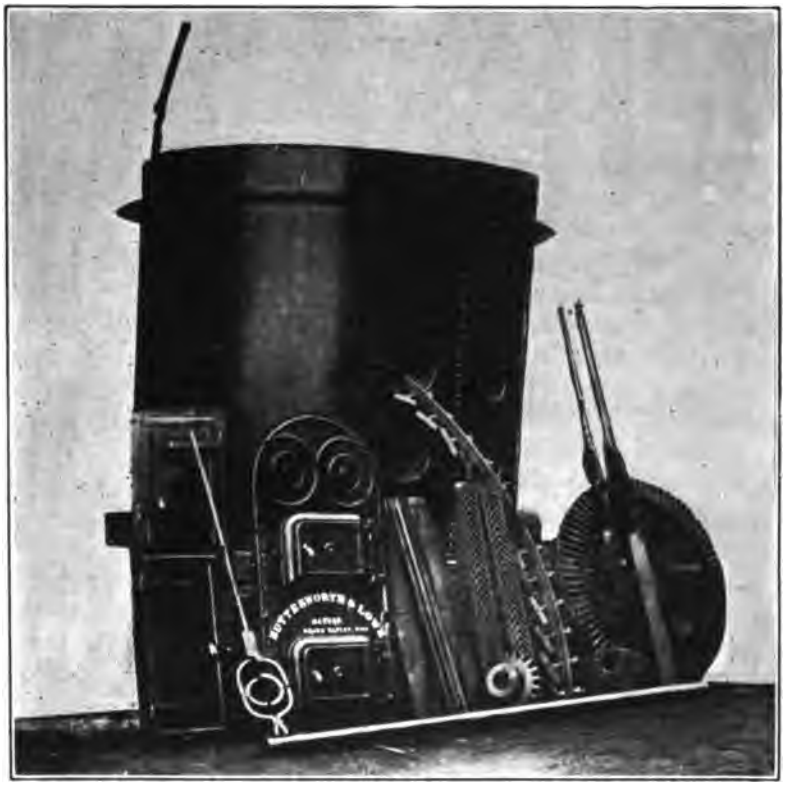


FIG. 11.—Four-flue kettle, with accessories, dismounted. (Butterworth & Lowe.)

ally converging at the top to meet the top rim of the kettle. The first floor of the mill is usually built around the kettle about a foot from the top, sometimes level with the top, to facilitate shoveling the raw material into the kettle, and the kettle with its supports is in the basement, with storage room for fuel conveniently arranged in front of the kettle. Ports are made through the side of the base ring, and the heat from the furnace is deflected by bridges around the surface

of the kettle, so that the heat may cover every part of the kettle, pass through the flues, and finally make exit through a regular stack.

At the top the kettle is covered with a sheet-iron cap having a movable door, through which the raw material is introduced, usually by a chute fed by an elevator.

The shipping-weight of an 8-foot kettle is about 15,000 lbs., and of a 10-foot kettle about 18 500 lbs. Their list prices are about $1200 and $1600, respectively.

FIG. 12.—Kettle with sectional bottom. (Des Moines Mfg. Co.)

The kettles are usually arranged in line and worked in pairs, with one feeding chute and one pit for calcined material for each pair. It is necessary that the material in the kettle be kept constantly agitated, and for this purpose a line-shaft carrying a 1-inch vertical pinion-wheel runs over the kettles and a 4-inch vertical shaft with a 5-inch horizontal crown-wheel runs from this to the bottom of each kettle, being supported by a saddle placed between the flues. At the bottom of the vertical shaft a curved cross is attached, to which are affixed movable

teeth with paddles, run at 15 revolutions per minute, which are so adjusted as to throw the material from the periphery to the center. From 10 to 25 H.P. are required to run one agitator. Should the agitation stop, or the teeth become broken, the material settles down on the bottom and, owing to the intense heat, the bottom is almost instantly melted through. The material, which when hot is very fluid, runs through like water and quenches the fire. Stoppage of the agitation can usually be detected by the calciner, who stands above and is supposed to watch the process of calcination constantly.

In burning plaster of Paris the temperature does not exceed 340° F., but when gypsite (gypsum earth) is used a higher temperature is required, averaging close to 396° F., probably owing to the foreign matters included in the gypsite.

In starting a kettle, the heat is gradually applied, and the crude material is gradually fed in and constantly agitated. This process is slow and requires some length of time, owing to the vast amount of mechanically held water which must be evaporated when the wet gypsum earths are used. Material is gradually added until the kettle is full, and as the temperature rises the contents boil violently, much like water, at 220°–230° F. (105°–110° C.). When the mechanically held water is evaporated the contents of the kettle settle. Further heating, however, brings on boiling again, at about 290° F. (= 143° C.), part of the water of combination being now driven off. The point at which the process is complete, 340°–396° F., is known to the expert calciner by the manner in which the material boils and by its general appearance, and at the proper moment the calciner allows the charge to blow out through a small gate at the bottom and in the side of the kettle, controlled by a lever. In plaster-of-Paris plants thermometers are commonly used to govern the temperature exactly, but in gypsite plants, whose raw material is not so uniform in composition, the proper point varies slightly and is usually best known by an experienced calciner.

The escaping steam is let off by means of a stack let into the sheet-iron cover of the kettle parallel with the smoke-stack, and this stack contains near its base a separator similar to the steam-separators, for the purpose of retaining the plaster-dust. It has been found by raising the iron cover about 18 inches and putting on proper sides, that it furnishes a chamber above the boiling material and greatly assists the escape of the steam from it.

From the kettle the hot material runs like water into a fire-proof pit. The kettles are usually run in couples so that one pit will do for two kettles: and one chute will do for two kettles in filling, as the kettles are run at slightly different periods. Each kettle contains a charge of

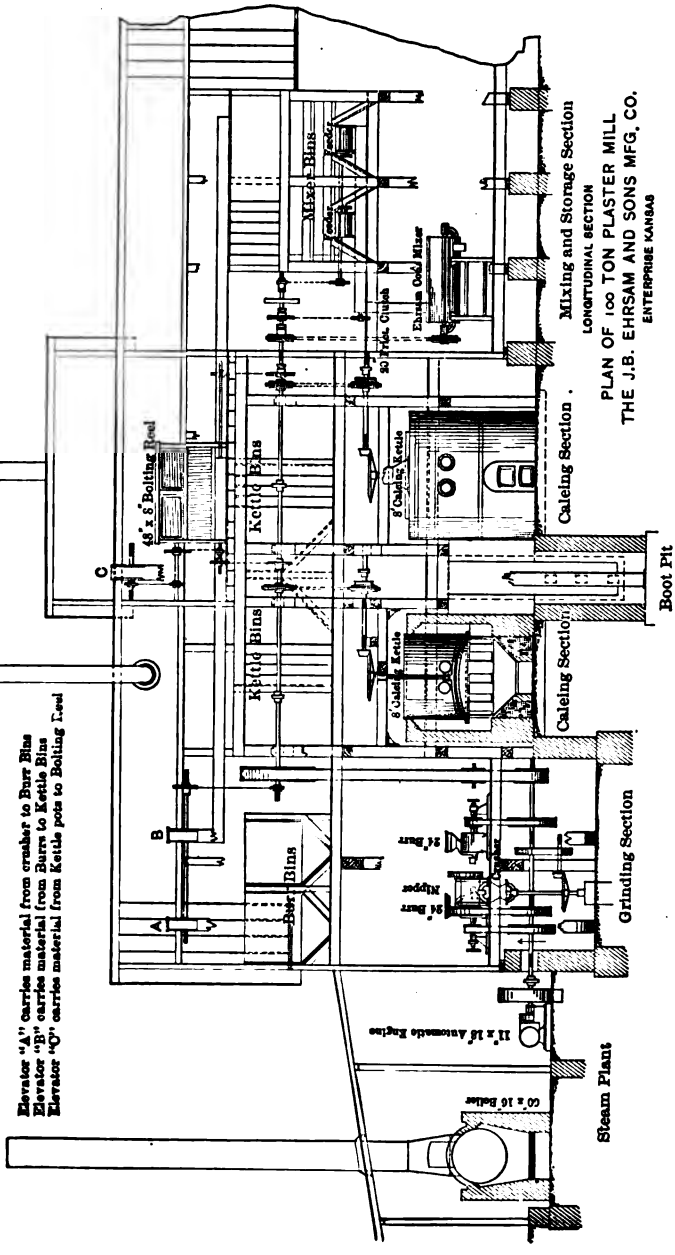

Elevator "A" carries material from crusher to Burr Bins
Elevator "B" carries material from Burrs to Kettle Bins
Elevator "C" carries material from Kettle pots to Bolting Reel
Steam Plant
Grinding Section
Caleing Section
Boot Pit
Caleing Section
Mixing and Storage Section
LONGITUDINAL SECTION
PLAN OF 100 TON PLASTER MILL
THE J.B. EHRSAM AND SONS MFG. CO.
ENTERPRISE KANSAS

FIG. 13.—Section of 100-ton plaster-mill, kettle process.

about five tons of manufactured material, and requires from two to three hours to calcine properly. After cooling slightly, the manufactured material is elevated into a revolving screen, which separates all small particles and foreign matter and renders the product uniform. The screenings which usually amount to from ½ to 1 per cent only are sent back to buhr-stones and reground. It is usual to have a series of screw-conveyors and elevators both in front of and behind the screen, so as to mix the material thoroughly. Owing to the temperature of the material, all conveyors, elevators, and interior linings must be of metal, and the screen is made of wire cloth. From the screen the material is conveyed to the storage-bins (which are usually arranged to hold 100 or 200 tons), of which there are several, so as to separate, if desired, the runs of different days. The material is usually allowed to fall from a screw at the top of the building, first, that it may spread out and let the different portions mix thoroughly, and, secondly, that it may cool in passing through the air.

Temperature and water determinations made by Slosson and Moudy during an actual run of the Laramie (Wyo.) plaster-plant are given in the following table. The kettle used carried a charge of about five tons, and the run was completed in about three hours. As shown by the water determinations the raw material (gypsum earth) carried a very large percentage of moisture in addition to its necessary water of crystallization. An analysis of the finished product, given below, shows that it is made from a very impure gypsum:

ANALYSIS OF LARAMIE PLASTER.

Lime sulphate ($CaSO_4$)	73.73%
Lime carbonate (aCO_3)	7.86%
Lime (CaO)	2.35%
Magnesium carbonate ($MgCO_3$)	3.04%
Silica (SiO_2)	5.50%
Alumina (Al_2O_3)	0.59%
Water (H_2O)	6.93%

TABLE 7.

TEMPERATURES IN CEMENT-PLASTER MANUFACTURE.

Time.		Temperature	Pounds Water Contained per 100 Pounds $CaSO_4$.	Percentage Water Contained.	Remarks.
Hrs.	Min.				
0	0	65° F.	59.93 lbs.	32.02%	Kettle charged.
2	0	310° F.	16.85 "	11.69%	Kettle full.
2	20	320° F.	13.66 "	9.69%	Charge boiling.
2	30	340° F.	12.41 "	8.34%	End of first boil.
2	50	390° F.	9.17 "	6.75%	Charge dumped.

Inspection of this analysis also proves that the plaster still carries a little more water than is theoretically correct. If these various points

be borne in mind, the temperature determinations given below will prove of value.

Actual equipment of kettle-process plants.—Plans of two kettle-process plants are given in Figs. 13 and 14. The following data, giving the actual equipments of a number of plaster-plants in the United States,

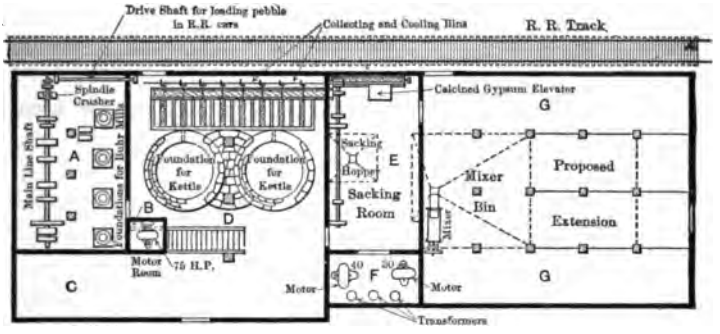


Fig. 8. FIRST FLOOR

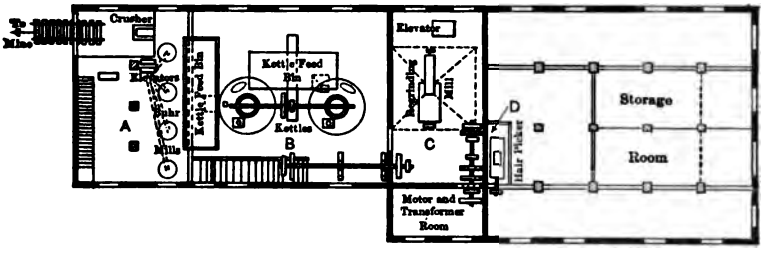


Fig. 4. SECOND FLOOR

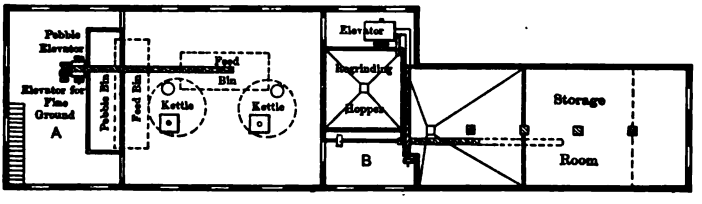


Fig. 5. THIRD FLOOR

FIG. 14.—Plan of Electric Plaster Co.'s mill, Blue Rapids, Kansas. (Engineering and Mining Journal.)

will serve to give a good idea of the relation of crushing machinery to number of kettles:

Plant No. 1.
- (*a*) 2 Butterworth & Lowe nippers.
- (*b*) 2 Butterworth & Lowe crackers.
- (*c*) 4 runs of 4-foot buhrstones and 1 Sturtevant vertical rock emery mill.
- (*d*) 4 10-foot kettles holding 10 tons each.
- (*e*) 8 runs of small buhrstones for regrinding finer grades of plaster.

Plant No. 2.	(*a*) 1 nipper.
	(*b*) 1 cracker.
	(*c*) 4 runs of buhrstones.
	(*d*) 3 10-foot kettles.
Plant No. 3.	(*a*) 1 Godfrey double nipper and cracker.
	(*b*) 3 Sturtevant vertical rock emery mills.
	(*c*) 3 10-foot kettles.
	(*d*) 2 runs of small buhrs for regrinding.
Plant No. 4.	(*a*) 1 nipper.
	(*b*) 1 cracker.
	(*c*) 2 runs of buhrstones and 1 Sturtevant vertical rock emery mill.
	(*d*) 2 10-foot kettles.
	(*e*) 3 runs of buhrstones for regrinding.
Plant No. 5.	(*a*) 1 nipper.
	(*b*) 1 cracker.
	(*c*) 2 runs of buhrstones.
	(*d*) 1 10-foot kettle.
Plant No. 6.	(*a*) 1 nipper.
	(*b*) 1 cracker.
	(*c*) 4 runs of buhrstones.
	(*d*) 2 8-foot and 1 10-foot kettles.
Plant No. 7	(*a*) 1 Stedman disintegrator.
	(*b*) 3 runs of buhrstones.
	(*c*) 3 10-foot kettles.
	(*d*) 2 runs of buhrstones for regrinding.
Plant No. 8.	(*a*) 1 Butterworth & Lowe nipper.
	(*b*) 1 cracker.
	(*c*) 4 runs of buhrstones.
	(*d*) 2 8-foot kettles.
	(*e*) 1 run of buhrstones for regrinding.
Plant No. 9.	(*a*) 1 Blake crusher.
	(*b*) 1 cracker.
	(*c*) 5 runs of burhstones.
	(*d*) 5 10-foot kettles.
Plant No. 10.	(*a*) 1 Blake crusher.
	(*b*) 2 runs of buhrstones.
	(*c*) 2 10-foot kettles.

Rotary-cylinder processes.—It will probably have been noted by the reader that both of the plaster-calcining processes previously described are discontinuous in operation and consequently expensive in both time and fuel. These defects of the oven and kettle processes are avoided in the rotary cylinder processes now coming into use in both America and Europe. In the United States a rotary process has been adopted in a number of New York plaster-plants, and has been in practical operation for a sufficiently long time to demonstrate its superiority over the kettle process. In Europe, to judge from a recent description of the German plaster industry, rotary plaster calciners have been used for a number of years and have proven entirely satisfactory.

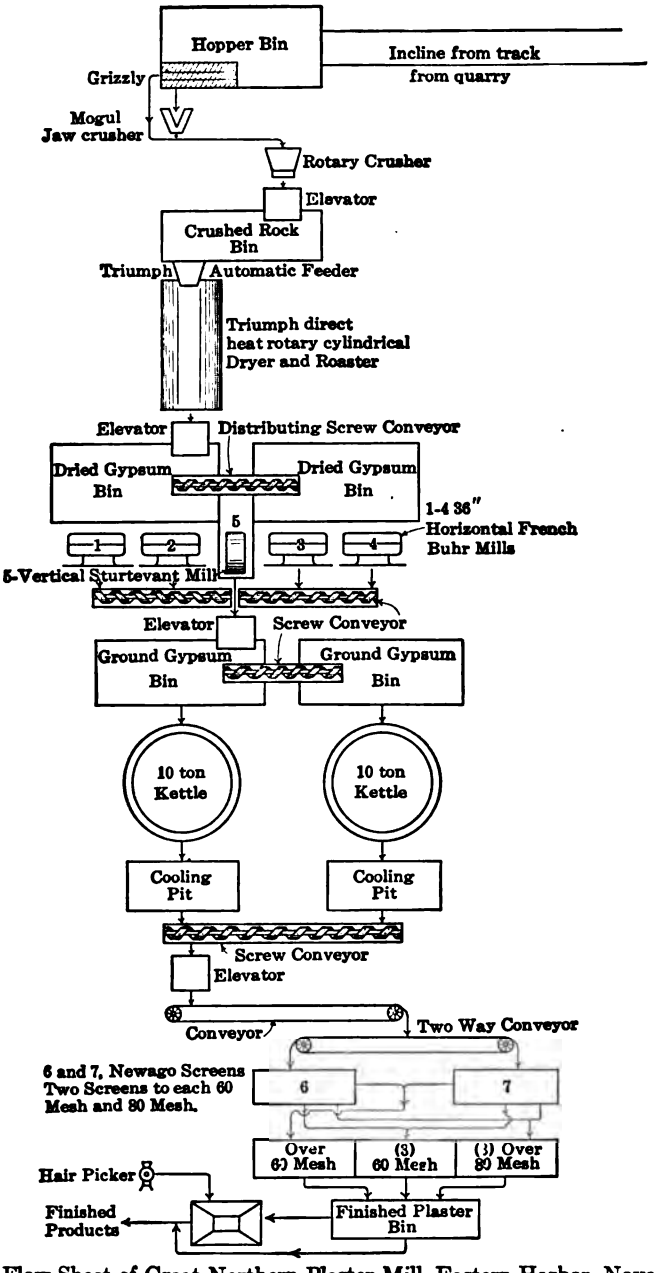
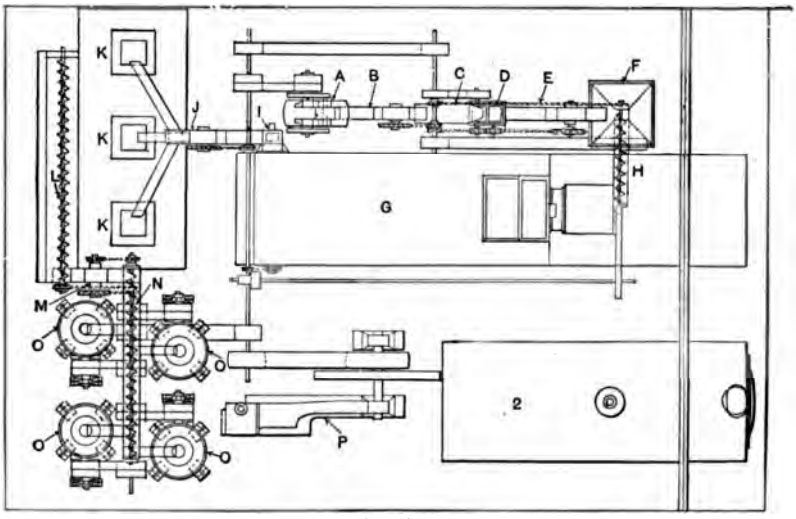


FIG. 15.—Flow Sheet of Great Northern Plaster Mill, Eastern Harbor, Nova Scotia. (After Coles.)

Cummer system.—Most of the American plants using the rotary calcination process have been equipped on the system devised by the F. D. Cummer & Son Co., of Cleveland, Ohio.

The plan of a New York plant using this process is shown in Fig. 16. This plant uses rock gypsum, and with the equipment shown produces 50 tons of calcined plaster per day of eleven hours, six men being required to operate the mill. The rock coming direct from the mine is delivered into the jaw crusher *A*, where it is reduced so as to pass a 2½-inch ring. Elevator *B* carries the crushed rock from crusher to screen *C*, which separates all material that will pass a 1-inch ring. The tailings from the screen pass through the rolls *D* and meet with the material which passes through the screen. All of the material now



PLAN

FIG 16.—Plan of plaster-mill equipped on Cummer rotary calcining system.

crushed to pass a 1-inch ring is carried by elevator *E* and delivered into bin *F*. From this bin the crushed rock is fed mechanically by feeder *H* into the Cummer rotary calciner *G*. In this machine most of the free moisture is eliminated, and the process of calcining also carried forward toward completion. The material delivered from the rotary calciner is steaming and heated to from 350° to 400° F., the exact temperature depending upon the nature and density of the rock. Elevator *J* carries the product from the calciner to the Cummer calcining-bins *K*, where it is allowed to remain about thirty-six hours. During this time the resident heat in the material completes the process of calcination, and the material is cooled, ready for the mills. The now calcined mate-

rial is mechanically discharged from the bins into elevator *M*, which carries it into the small bins situated over the mills *O*. From the mills the conveyor *R* delivers the pulverized material into screen *S*. The finished material is sacked at *T*. The tailings from the screen are spouted into elevator *M* and returned to the mills.

The calcining-bins noted above are an integral part of the Cummer process. These bins are built preferably of brick and are lined with paving brick, so that they will not absorb the moisture given off from the gypsum rock during calcination. Three bins are required for each plant, and the capacity of each bin is equal to the daily output of the plant. By the use of three bins a continuous process is obtained. One bin is being discharged of its cooled calcined material while the process of calcination is being completed on the material in the second bin, and the third bin is being filled with material from the rotary calciner.

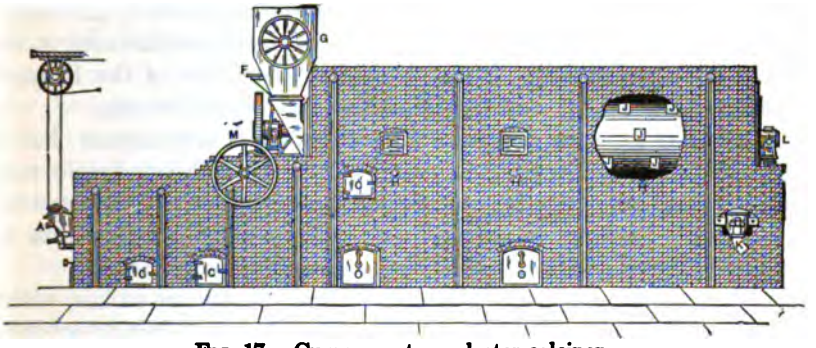


FIG. 17.—Cummer rotary plaster-calciner.

These bins are so constructed that the material in process of calcination is thoroughly ventilated, which allows the heat carried by the material from the rotary calciner to rapidly disseminate itself through the mass and complete the calcining process. While the resident heat in the material is acting upon it, practically no circulation of air through the material is allowed, but as soon as the process of calcining is completed, air at atmospheric temperatures is freely circulated through the mass and the calcined gypsum is rapidly cooled. Each bin is equipped with a simple device which mechanically discharges the material regularly and at any speed desired.

A dust-chamber located above the rotary calciner catches the most finely ground plaster, which is marketed for dental plaster and other special purposes.

The Cummer rotary calciner is shown in section in Fig. 17. Its operation is as follows:

The gypsum rock is fed through a hopper, *F*, into a cylinder set

on a slight incline rotating on trunnioned bearings within a brick chamber. The material passes slowly down the cylinder (owing to its inclination and rotation), being thrown about by lifting-blades attached to the inside of the cylinder. It is discharged at *K*, having been subjected during its passage to the heated fuel gases, whose admission and handling will next be described.

The hot gases from the furnace are drawn by the fan *G* into the brick chamber surrounding the cylinder. Cold air is introduced through the registers *E* and *O* and mixed with the furnace gases in such proportions as to give the desired temperature. These gases are drawn into the cylinder through the hooded openings *J* and pass through it in a direction opposite to that taken by the wet material. Pyrometers for control of the temperature may be placed in the holes *H* in the masonry.

Mannheim system.—A German plaster-plant using a rotary calcining system has recently been described * in considerable detail, and seems worthy of attention as presenting certain interesting differences to the system discussed above. The mill in question is that of the Rhenish Gypsum Company, located at Mannheim, in Rhenish Prussia.

The crude gypsum is passed through crushers and nippers, but is not finely powdered previous to calcining. " When the material comes from the crushers and nippers it varies in size from the finest powder to fragments as large as an ordinary hickory-nut. Varying thus in size, the material goes directly to the calciner."

" The calciner consists of a fire-box with an automatic stoker, which is placed in front of and connected with a chamber containing a rotating cylinder. Above this cylinder is a chamber called the ' forewarmer,' through which a spiral conveyor passes from end to end. A pipe leads from the rotating cylinder to the forewarmer and connects at the other end with the chimney. Connected with the fire-box is a fan by which a forced draft is secured. The fire-box is heated to a high temperature, and the fuel gases, forced by the fan, pass through the rotating cylinder and then through the forewarmer. The crude gypsum is carried by bucket elevators from the crushers to a bin above the calciner and thence it flows by gravity into the forewarmer, through which it is carried by the spiral conveyor. It then falls directly into the rotating calciner below. Shelves or buckets on the inside of the cylinder pick up the material and elevate it as the cylinder rotates. When the material nears the top the slant of the shelves is so great that it falls again to the bottom. The strong draft of hot air passing through the cylinder from the fire-box strikes the gypsum as it falls and moves the fragments toward the rear with a velocity directly † proportional to their size.

* Wilder, F. A. Vol. 12, Iowa Geological Survey, pp. 213-216.

† Evident misprint for " inversely."

The coarser material moves much more deliberately and thus is exposed to the heat longer than the finer and more readily calcined particles. In this way, though the material entering the rotating cylinder varies greatly in fineness, the coarser material is sufficiently calcined and the finer is not overburned. All of the heat has not been exhausted in gassing through the rotary cylinder and this is for the most part saved by forcing the air, after it leaves the cylinder, through the forewarmer. In this process the heat is so completely utilized that the air and furnace gases pass to the chimney with a temperature of only 80° C. Between the forewarmer and the chimney the dust-chamber is located. Here all of the finer particles are allowed to settle and the air passes on to the chimney practically free from dust. To calcine one ton of gypsum by this method experience has demonstrated that on the average only 100 lbs. of rather inferior bituminous coal are required. An automatic recorder indicates constantly the heat of the rotary cylinder, and this, with the mechanical stoker, insures an even temperature during the entire process of calcining. From the rotary cylinder the gypsum is again elevated to the floor above and passes through a spiral conveyor which is surrounded by a water-jacket. Here the plaster is cooled and passes on to the sieves. That portion of the plaster which does not need further grinding is separated by the sieves and the rest goes to the vertical mills."

The process shows economy in fuel, labor, and power over the older methods. On the other hand, " a limited amount of soot settles in the plaster, and it is slightly coated with calcium sulphide, due to the reaction on the gypsum of the sulphur present in the coal. For ordinary building purposes, however, these do not injure the plaster."

Addition of retarders and accelerators.—It is now the common practice for plaster manufacturers to add retarders to their product, in order to prevent its setting too rapidly for the convenience of the workman. The general discussion of the character and effects of retarders and accelerators can best be taken up in the following chapter. At present it is only necessary to state that the retarder is best added after the plaster is entirely cool, as otherwise most retarders will melt and form lumps in the plaster. From 2 to 15 lbs. of retarder are usually added to the ton of plaster, and the mixing is generally accomplished in a Broughton mixer or some similar device.

The following data relative to the Broughton mixer, which is shown in Fig. 18, are taken from the catalogue of the Des Moines Manufacturing and Supply Company, and will serve to give some idea of the capacity, cost, etc., of the machine.

Wall-plaster.—An ordinary wall-plaster contains, in addition to whatever retarder may be necessary, a certain percentage of finely picked

TABLE 8.

SIZES, CAPACITY, ETC., OF BROUGHTON MIXERS.

Style	A–1	A	B–1	B–2	B–3
Capacity of hopper, lbs.	1800–2000	1000–1400	600	500	250
Bag-holders, number	6	5			
Product per day, 10 hours, tons	60–90	35–50	35	15	7½
Size of pulleys, inches	30×12	24×8	24×8	20×6	16×4
Revolutions per minute	150	150	175	160	160
Horse-power required	18–22	8–12	8–12	5–7	3–4
Shipping weight, lbs.	7300	4750	3800	2300	

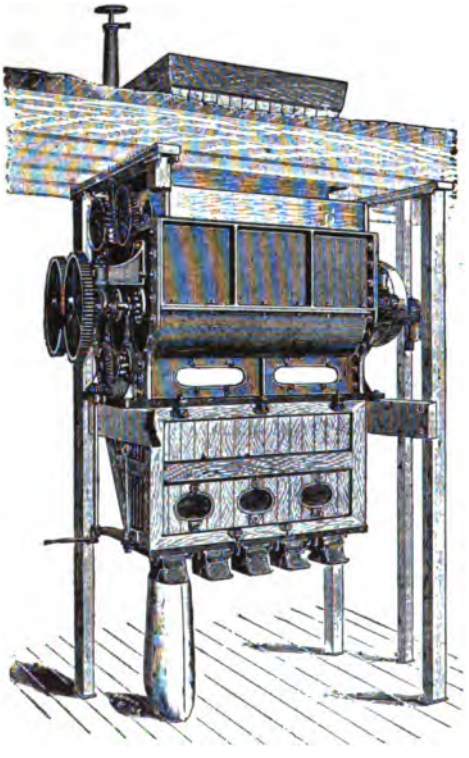


FIG. 18.—Broughton mixer.
(Des Moines Mfg. Co.)

FIG. 19.—Hair-picker.

hair or other fiber. In order to insure thorough mixing with the plaster the hair is first picked to pieces in a hair-picker, which is usually a device of the toothed-drum type revolving at high speed. The hair is then added to the plaster in the proportions of 1½ to 3 lbs. hair per ton of plaster and the materials are fed to the mixer.

The hair-picker shown in Fig. 19 is run at a speed of 600 revolutions per minute and will disintegrate 5 to 6 bales of hair per hour.

Wood fiber is often used as a substitute for hair, cottonwood giving a particularly serviceable fiber for this use. The log is barked by hand or machine and cut into sections 20 inches or so in length. These are then placed in a fiber machine, which will usually take pieces 6 to 15 inches in diameter. The fiber is torn off by revolving toothed cylinders between which the log is pressed. One machine will cut enough fiber in nine or ten hours to make 30 to 40 tons of plaster. The usual mix consists of 75 to 150 lbs. wood fiber to one ton of calcined plaster.

Plaster are usually packed in jute sacks containing 100 lbs. or in paper bags containing 80 lbs. An extra charge of 10 cents is commonly made for each jute sack, rebated on the return of the sack. As the sacks may cost the mill 4 to 6 cents each, any sacks not returned furnish a fair profit. A charge of 50 cents per ton of plaster is usually made for packing in paper bags, which are not returnable.

Costs of plaster-manufacture.—An estimate of the cost of plaster-manufacture at Kansas mills, made in 1897 by G. P. Grimsley,* follows:

COST OF PLASTER-MANUFACTURE PER TON.

Mining costs	$0.80
Fuel at mill	0.30
Labor at mill	0.50
Office force and sales agents	1.25
Total cost of plaster per ton	$2.85

Setting aside the question of cost of " office force and sales agents," which varies greatly in different mills, the estimate given above appears to the writer to be very high for mining costs, rather below the average for fuel costs, and about the maximum for labor. The following estimates of cost of manufacture by the kettle process have, therefore, been prepared as giving, in the writer's opinion, fairly close limiting values on unit values as during the 1900–1910 decade.

	Max.	Min.	Average.
Mining or quarrying 2400 lbs. gypsum	$0.72	$0.12	$0.30
Power fuel at mill, 75 to 125 lbs. coal	0.19	0.05	0.10
Kiln fuel at mill, 225 to 325 lbs. coal	0.49	0.15	0.30
Labor at mill	0.50	0.30	0.40
Total cost per ton plaster at mill	$1.90	$0.62	$1.10

The rotary process of plaster calcination has not been used at enough plants to give accurate limiting figures of costs, but the following estimates are believed to be fairly close:

	Max.	Min.
Mining or quarrying 2400 lbs. gypsum	$0.72	$0.12
Power fuel at mill, 50 to 80 lbs. coal	0.12	0.04
Kiln fuel at mill, 150 to 200 lbs. coal	0.31	0.10
Labor at mill	0.30	0.18
Total	$1.45	$0.44

* Mineral Industry, vol. 7, p. 392.

Analyses of gypsum used in actual practice.—The following analyses of both rock gypsum and gypsite (gypsum earth), taken from various sources, will be fairly representative of the materials used for plaster at different plants. For comparison it is well to recollect that a theoretically pure gypsum would consist of lime sulphate 79.10 per cent, water 20.90 per cent, and would contain no silica, alumina, iron oxide, lime carbonate, or magnesium carbonate.

Tables 9 and 10 following gives analyses of gypsums from localities (with few exceptions) solely in the United States. Tables 25 and 28 on later pages gives analyses of French and Canadian gypsums.

TABLE 9.

ANALYSES OF ROCK GYPSUM USED FOR PLASTER.

+	Silica (SiO_2).	Alumina (Al_2O_3) and Iron Oxide (Fe_2O_3).	Lime Carbonate ($CaCO_3$).	Magnesium Carbonate ($MgCO_3$).	Lime Sulphate ($CaSO_4$).	Water (H_2O).
1	....	....	....	....	79.40	20.30
2	0.35	0.12	0.10	0.25	78.73	20.52
3	0.65	0.17	1.53	0.39	79.30	18.84
4	0.40	0.19	0.25	0.35	78.10	20.36
5	0.35	0.12	0.56	0.57	78.40	19.96
6	1.18	0.15	0.36	0.52	78.04	20.00
7	0.52	0.26	1.87	2.06	75.84	19.47
8	0.34	0.16	1.68	1.30	76.98	19.63
9	0.41	0.29	0.55	0.61	78.25	19.70
10	0.55	0.23	0.86	0.47	78.11	19.54
11	0.38	0.16	....	0.96	77.81	20.37
12	0.19	0.10	1.43	0.34	77.46	20.46
13	0.05	0.08	....	0.11	78.51	20.96
14	n. d.	n. d.	n. d.	n. d.	77.11	19.00
15	tr.	0.54	n. d.	n. d.	76.26	20.84
16	1.24	0.50	2.38	....	77.19	19.03
17	0.56	tr.	1.86	....	77.77	20.28
18	0.68	0.16	n. d.	n. d.	78.08	20.14
19	0.46	0.29	n. d.	n. d.	78.96	20.00
20	0.91	0.60	n. d.	n. d.	78.73	19.70
21	0.10	0.70	....	....	79.26	19.40
22	0.02	0.55	....	....	80.14	19.07
23	0.49	0.46	....	....	77.94	20.85
24	1.68	1.95	....	....	72.06	21.30
25	0.10	0.10	....	....	78.55	20.94
26	0.11	....	1.07	....	98.42	20.43

1. Gypsum Station, Calif.
2. Blue Rapids, Kansas } used at Great Western Plaster-mill.
3. " " " }
4. " " " }
5. Dillon, Kansas.
6. " "
7. Hope, Kansas.
8. " "
9. " "
10. Solomon, Kansas.
11. " "
12. Medicine Lodge, Kansas.
13. Alabaster, Michigan, used at Western Plaster Works.
14. Grand Rapids, Mich.
15. " " "
16. " " "
17. Alabaster, Mich.
18. Near Sandusky, Ohio.
19. " " "
20. " " "
21-24. Saltville, Virginia.
25. Hillsboro, New Brunswick.
26. Baddeck Bay, Novn Scotia.

TABLE 10.

ANALYSES * OF GYPSITE (GYPSUM EARTH) USED FOR PLASTER.

	Silica (SiO_2).	Alumina (Al_2O_3) and Iron Oxide (Fe_2O_3).	Lime Carbonate ($CaCO_3$).	Magnesium Carbonate ($MgCO_3$).	Lime Sulphate ($CaSO_4$).	Water (H_2O).
1	10.67	0.60	10.21	1.10	59.46	16.59
2	2.17	0.24	2.66	0.95	75.11	19.40
3	2.31	0.37	11.71	0.52	67.91	17.72
4	4.54	0.54	5.07	0.59	71.57	17.82
5	13.50	1.05	7.50	0.76	60.27	17.05
6	7.65	0.52	8.11	0.63	64.72	18.39
7	3.62	0.45	4.09	0.34	71.94	19.87
8	15.08	0.44	7.02		60.51	17.46
9	10.23	1.12	11.77	0.94	58.75	17.10
10	34.35	4.11	8.14	10.52	34.38	8.50
11	9.73	0.78	4.32	tr.	68.29	16.88
12	3.06	0.34	11.03	0.90	67.32	17.24
13	4.25	0.53	3.56	0.21	69.51	20.82
14	4.82	0.79	4.52	0.34	68.14	20.41
15	15.76	0.49	5.14		59.93	18.64
16	8.78	1.98	7.25	1.12	58.25	20.66
17	7.68	0.89	7.39	1.76	63.37	17.77
18	11.78	1.87	7.37	1.00	59.56	18.25
19	6.33	0.53	13.68	0.88	55.71	19.23
20	5.14	0.67	7.36	1.12	66.64	19.95
21	12.13	0.99	3.57	0.88	64.63	16.75
22	17.10	2.04	7.71	1.24	56.58	15.16
23	3.18	0.95	6.18	0.33	69.70	19.44
24	6.49	1.04	6.96	0.27	65.97	18.56
25	17.95	1.43	n. d.	n. d.	61.00	18.44

* The analyses in this table are mostly by Bailey and his associates and are quoted from vol. 5, Kansas Geol. Survey.

1. Marlow, Oklahoma, used for "Royal" brand plaster.
2. Mulvane, Kansas.
3. Burns, Kansas.
4. Tinkler, Kansas, used at Gypsum City.
5. Gypsum City, Kansas, surface of bed, used for "Acme" brand plaster.
6. Gypsum City, Kansas, center of bed, used for "Acme" brand plaster.
7. Gypsum City, Kansas, average, used for "Acme" brand plaster.
8. Gypsum City, Kansas, quick-setting gypsite, used for "Acme" brand plaster.
9. Longford, Kansas, used by Salina Cement Plaster Co.
10. Salina, Kansas.
11. " "
12. Rhoades, Kansas.
13. " " , 4 feet from surface.
14. Rhoades, Kansas, 8 feet from surface.
15. " " , bottom of bed.
16. " " , average of 1 acre.
17. " " , average of 8 samples 2½–3½ feet depth.
18. Rhoades, Kansas, small deposit.
19. " " , material very slow setting.
20. Rhoades, Kansas, average as used in plaster-plant.
21. Dillon, Kansas, used by Salina Cement Plaster Co.
22. Dillon, Kansas, used by Dillon Cement Plaster Co.
23. Dillon, Kansas, used by Dillon Cement Plaster Co.
24. Dillon, Kansas, used for "Agatite" plaster.
25. Okarche, Oklahoma.

Inspection of the analyses quoted in Tables 9 and 10 will show that the rock gypsum used at plaster plants is usually very pure. Until very recently no attempt has been made to utilize the impure gypsum

rock which forms such a large proportion of the New York deposits, though there is no technologic reason for not using it. The analyses of gypsite or gypsum earth, on the other hand, are mostly representative of very impure materials, carrying large percentages of sand, clay, and fragments of limestone. The presence of these impurities in the natural raw material is a matter of technologic importance, for the calcined plaster made from such impure materials is naturally very slow setting.

References on plaster-manufacture.—The following papers deal largely with the manufacturing side of the gypsum industry.

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Grimsley, G. P. and Bailey, E. H. S. Special report on gypsum and gypsum-cement plasters. Vol. 5, University Geological Survey of Kansas, 183 pp. 1899.

Grimsley, G. P. Gypsum in Michigan, Reports Mich. Geol. Survey, vol. 9, pt. 2. 1904.

Leduc et Chenu. Chaux, Ciments, Platres. Paris, 1912.

Newland, D. H. and Leighton, H. Gypsum deposits of New York. Bull. 143, N. Y. State Museum, Albany, 1910.

Parsons, A. L. Recent developments in the gypsum industry in New York State. 20th Ann. Rep. New York State Geologist, pp. 177–183. 1902.

Slosson, E. E. and Moudy, R. B. The Laramie cement plaster. 10th Ann Rep. Wyoming College of Agriculture and Mechanics.

Wilder, F. A. Geology of Webster County, Iowa. Vol. 12, Reports Iowa Geological Survey, pp. 63–235. 1902.

Wilder, F. A. The gypsum industry of Germany. Vol. 12, Reports Iowa Geological Survey, pp. 192–223. 1902.

Wilder, F. A. Present and future of the American gypsum industry. Engineering and Mining Journal, vol. 74, pp. 276–278. 1902.

Wilkinson, P. The technology of cement plaster. Trans. Amer. Inst. Mining Engrs., vol. 27, pp. 508–519.

CHAPTER III.

COMPOSITION, PROPERTIES, AND TESTS OF PLASTERS.

In the present chapter the chemical composition and physical properties of plaster of Paris and cement plasters will be taken up in the order named.

Chemical Composition.

Theoretical composition.—A theoretically pure plaster of Paris, being a definite chemical compound ($CaSO_4+\frac{1}{2}H_2O$), would have the composition: lime sulphate, 93.8 per cent; water, 6.2 per cent. This composition is approached quite closely in plasters made from a pure rock gypsum.

Cement plasters, as has been described on earlier pages, can be made in two different ways, which give two different products so far as composition is concerned. (1) Cement plasters may be made by adding retarders to a pure plaster of Paris. As the retarder is organic matter and rarely amounts to over 1 per cent of the total mass the resulting product will on analysis differ very little from the plaster of Paris of which it was made. (2) Cement plaster may also be made by burning an impure gypsum, with or without the addition of retarder. In this case analysis would show the presence of a large percentage of clayey matter, etc., and a cement plaster of this type will therefore have a composition very different from that of a pure plaster of Paris. Examples of both these types will be found in Table 11, opposite.

Actual composition of cement plasters.—As noted earlier, a cement plaster when ready for sale differs from the gypsum of which it was made only in the loss of water and the addition of a very small proportion ($\frac{1}{10}$% to 1%) of retarder. The difference between the analyses of any two samples or brands of cement plaster will therefore depend on the difference in composition between the gypsums from which the two samples were made.

TABLE 11

ANALYSES OF CEMENT PLASTERS.

	Silica (SiO_2).	Alumina (Al_2O_3) and Iron Oxide (Fe_2O_3).	Lime Carbonate ($CaCO_3$).	Magnesium Carbonate ($MgCO_3$).	Lime Sulphate ($CaSO_4$).	Water (H_2O).
1	39.55	0.61	5.79	0.54	46.99	6.42
2	1.00	0.33	1.50	0.75	88.50	8.00
3	1.20	0.20	1.68	1.18	89.42	6.86
4	4.27	0.47	3.07	1.47	83.55	6.67
5	12.04	1.50	8.44	2.24	71.74	4.80
6	0.97	0.30	0.04	1.28	89.98	7.29
7	0.85	0.16	0.94	1.28	91.07	6.33
8	11.97	0.67	8.11	0.73	71.43	6.98
9	14.67	1.05	10.07	0.95	66.91	6.41
10	5.52	0.40	12.00	1.74	74.43	6.99
11	9.73	0.62	11.30	0.65	72.42	5.49
12	19.43	0.53	9.59		64.42	6.21
13	13.29	0.71	4.77	1.91	73.67	5.78
14	23.38	2.42	n. d.	n. d.	69.41	5.66
15	7.43	0.12	5.07	tr.	78.66	8.49

1. Florence, Colorado.
2. Rhoades, Kansas.
3. Blue Rapids, Kansas, "Crystal Rock" brand, Great Western Plaster Co.
4. Springdale, Kansas, "Roman" brand.
5. " " "Acme" "
6. Blue Rapids, Kansas, "Sunshine" finishing plaster, Great Western Plaster Co.
7. Blue Rapids, Kansas, "Ivory" finishing plaster, Blue Valley Plaster Co.
8–12. Blue Rapids, Kansas, "Acme" cement plasters.
13. Okarche, Oklahoma.
14. " "
15. Quanak, Texas.

Weight and Fineness of Plasters.

Weight and specific gravity.—Pure gypsum, before calcination, has a specific gravity of 2.30 to 2.33, corresponding to a weight of about 143⅓ lbs. per cubic foot, while the specific gravity of plaster of Paris is about 2.57. The apparent specific gravity of cement plaster in bulk is 1.81.* This would correspond to a weight of about 113 lbs. per cubic foot if no allowance were made for air-spaces. According to the results † of Slosson and Moudy on Laramie plaster, a bushel weighed 64 lbs., and a block composed of 50 parts sand and 100 parts plaster, after being set and dried, gave a specific gravity of 1.5, corresponding to a weight of 93⅓ lbs. per cubic foot.

Fineness of calcined plasters.—A number of cement plasters, wall-plasters, and allied products from Iowa, Kansas, Texas, and Oklahoma

* Wilder, F. A. Vol. 12, Iowa Geological Survey, p. 139.

† Tenth Ann. Rep. Wyoming Agric. and Mech. College.

were tested for fineness by Prof. Marston in 1900. The results * of these tests are given in the following table. The tests were made on material purchased in the open market.

TABLE 12.

FINENESS OF CALCINED PLASTERS.

Per cent passing sieve.

Meshes per linear inch	74	100	200
Average diameter of largest particle passing	.00901"	.00452"	.00271"
Gypsum, ready for burning, Stucco Mills, Ft. Dodge, Iowa	68.3	60.0	44.0
Stucco, Ft. Dodge Plaster Co., Ft. Dodge, Iowa	71.9	66.2	49.3
Baker stucco, Kansas	72.9	58.3	39.5
Kallolite stucco, Cardiff Gypsum Plaster Co., Ft. Dodge, Iowa	69.1	63.8	50.2
Baker plaster, Kansas	68.2	58.7	28.2
Mineral City wall-plaster, Ft. Dodge, Iowa	72.1	65.4	49.1
Oklahoma Cement Plaster Co., Okarche, Oklahoma	77.8	70.2	51.3
Flint wall-plaster, Iowa Plaster Association, Ft. Dodge Iowa	72.4	64.2	48.1
Acme wall-plaster, Acme, Texas	74.6	69.2	56.6
Kallolite wall-plaster, Cardiff Gypsum Plaster Co., Ft. Dodge, Iowa	70.8	65.5	53.5
Stonewall-plaster, Ft. Dodge Plaster Co., Ft. Dodge, Iowa	72.4	66.1	54.0
Duncomb wall-plaster, Duncomb Stucco Co., Ft. Dodge, Iowa	63.8	57.8	43.6

Tensile and Compressive Strength.

Methods of testing plasters and similar products have never been standardized, and the result is that each investigator applies such tests as he may deem advisable. In general the practice has followed closely along the lines of cement-testing.

Tensile strength of plasters.—In making the experiments discussed below, Professor Marston "mixed the plaster or stucco thoroughly, by hand, with water. The mortar was then placed in standard (Am. Soc. C. E.) cement briquette molds and packed with the finger. The surface of the briquette was smoothed with a trowel. As soon as the briquettes were sufficiently set, which usually took about three hours, the molds were removed." Some of the briquettes were kept in air and some in water for various lengths of time, and they were finally

* Iowa Geological Survey, vol. 12, p. 162.

broken in a Fairbanks cement-testing machine. Preliminary tests, using various percentages of water, showed that 30 to 35 per cent of water gave the maximum strength of briquettes. As 35 per cent gave a mixture that was more readily handled in the making of briquettes than the 30 per cent mixture, it was adopted for the final series of tests whose results follow.

A series of 220-day tests were made, but the results are of little value, because the briquettes were allowed to stand in very moist air between the 28- and 220-day periods, and therefore all showed a marked falling off in strength. For this reason the results of the 220-day tests are omitted here.

TABLE 13.

FINENESS OF PLASTERS TESTED.

	Per Cent Passing Sieve.		
	74-mesh	100-mesh.	200-mesh.
Crystal Rock plaster	73.7	12.3	2.5
" " "	74.3	55.2	4.3
Flint plaster, fresh	66.4	58.6	55.7
" " old	81.9	68.7	52.2
German stucco	90.5	85.0	19.8

TABLE 14.

TESTS OF TENSILE STRENGTH AND EFFECT OF SAND.

	Neat.				1 Plaster, 1 Sand.				1 Plaster, 2 Sand.				1 Plaster, 3 Sand.			
	1 Day.	1 Week.	4 Weeks.	3 Months.	1 Day.	1 Week.	4 Weeks.	3 Months.	1 Day.	1 Week.	4 Weeks.	3 Months.	1 Day.	1 Week.	4 Weeks.	3 Months.
Crystal Rock plaster, unsuited	228	393	445	426	87	320	368	370	55	203	212	255	35	148	145	156
Crystal Rock plaster, sifted	...	...	...	...	...	...	...	...	57	231	229	229				
Flint plaster, fresh, unsifted	135	310	402	...	104	303	362	...	64	206	203	...	39	132	139	
Flint plaster, fresh, sifted	...	...	...	...	...	...	...	...	61	233	242					
Flint plaster, old, unsifted	155	353	433	...	...	...	...	...	26	109	123					
Flint plaster, old, sifted	...	...	...	...	...	...	...	...	49	205	256					
German stucco	300	461	461	...	...	...	...	...	119	336	356	...	75	303	252	

The results of a later series of tests carried * out by Prof. Marston are given below. Most of the tests were made on fresh plaster as marketed. A few, however, noted in the table as " sifted," were made on that portion of the plaster which passes through a 100-mesh sieve. Plaster four years old was also tested, as noted in the table. All the figures given are the averages of from 3 to 15 separate tests.

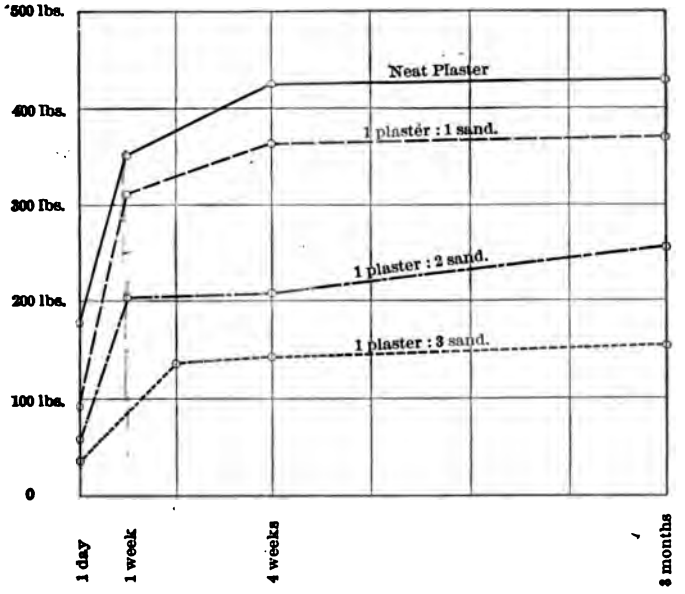

FIG. 20.—Effect of sand on tensile strength of plasters. (Marston.)

These tests appear to show † that

(*a*) Cement plasters and stuccos attain almost their full strength at the end of one week, showing little further gain at three months.

(*b*) The portion of the plaster which passes a 100-mesh sieve is stronger than the coarser portions, and the higher strength of fine plaster is shown better in sand mixtures than when tested neat.

(*c*) The value of fine grinding is further emphasized by the high results shown by the German stucco, which seems to have been the most finely ground of all, though the values of fineness given are not quite consistent.

* Iowa Geol Survey, vol. 12, pp. 232–235.

† The conclusions here drawn from these tests are those of the writer: For Professor Marston's conclusions, which do not entirely agree with mine, reference should be made to the original work.

TABLE 15.

RESULTS OF TENSILE TESTS OF PLASTERS.

Material.	Tensile Strength per Square Inch.			
	Kept in	1 Day.	7 Days.	28 Days.
Stucco, Fort Dodge, Iowa	Air	226	204	329
	"	219	210	438
	Water	195	139	187
	"	208	154	200
Kallolite plaster, Ft. Dodge, Iowa	Air	291	188	379
	"	186	230	245
	Water	175	185	168
	"	189	170	209
Duncomb plaster, Ft. Dodge, Iowa	Air	211	184	375
	"	208	220	360
	Water	192	172	180
	"	202	175	186
Mineral City plaster, Ft. Dodge, Iowa	Air	...	190	237
	"	...	301	437
	Water	215	203	195
	"	192	196	205
	"	195		
Stone plaster, Ft. Dodge, Iowa	Air	131	170	483
	"	144	228	470
	Water	187	163	182
	"	214	193	148
Flint plaster, Ft. Dodge, Iowa	Air	192	224	348
	"	204	217	285
	Water	188	207	158
	"	214	205	163
Acme plaster, Acme, Texas	Air	107	128	333
	"	131	175	303
	Water	82	20	151
	"	111	112	154
Stucco, Baker Stucco Co., Kansas	Air	227	236	468
	"	221	208	461
	Water	216	223	154
	"	226	206	181
Plaster, Baker Stucco Co., Kansas	Air	181	195	465
	"	134	218	286
	Water	183	196	195
	"	185	162	215

Compression tests and effects of sand.—A valuable series * of experiments were carried out during 1899–1900 by Profs. Slosson and Moudy on the compressive strength of plasters, both neat and mixed, with varying properties of sand. Most of the material used for these tests was a cement plaster manufactured at Laramie, Wyo., the tests being made before the addition of retarder to the plaster.

The material was molded into 2-inch cubes and crushed in a Riehlé self-registering machine after the cubes had been exposed to the air

* Tenth Ann. Rep. Wyoming Agric. and Mech. College, 1900.

for one week. "The sand used was obtained from the Laramie River and was composed of sharp-angled granitic fragments. It was sifted through a millimeter sieve."

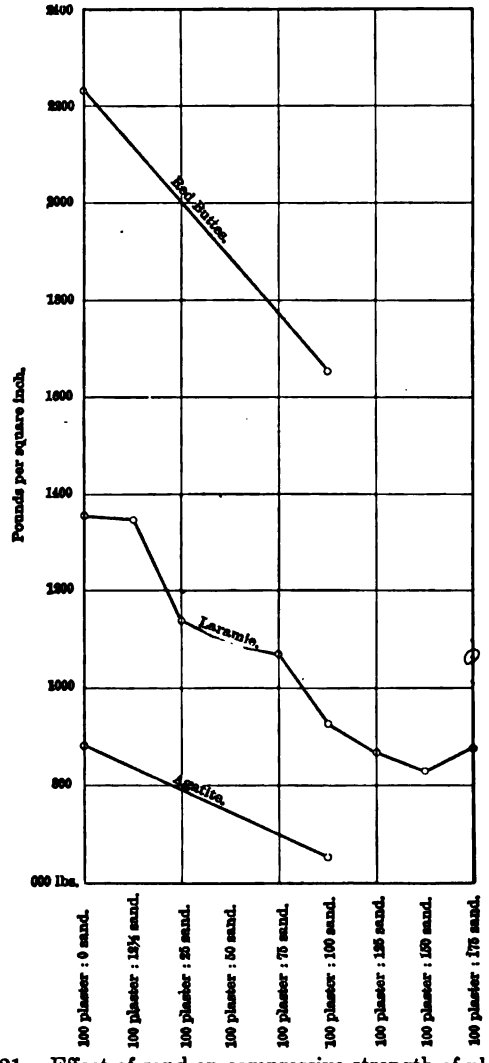

FIG. 21.—Effect of sand on compressive strength of plaster.

Adhesive tests of plasters.—The adhesive tests in Table 17 were made by Prof. Marston "by taking pieces of No. 2 paving-brick from Des Moines and grinding them on the emery-wheel so as to make approximately 1-inch cubes. Each cube had one face carefully

trued to give a cross-section exactly 1 inch square. These pieces of paving-brick were placed in the cement briquette molds with this true surface exactly at the middle of the mold. The plaster or stucco was placed to fill the other half of the mold, while the half in which the piece of brick was placed was filled with neat Portland-cement mortar."

TABLE 16.

EFFECT OF SAND ON COMPRESSIVE STRENGTH OF PLASTERS.

Kind of Plaster.	Parts by Weight.			Number of Tests.	Strength, 2-inch Cube.	Lbs. per Sq. In.
	Plaster.	Sand.	Water.			
Laramie plaster, no retarder	100	0	56	4	5435	1358¾
" " " "	100	12½	56	2	5340	1357½
" " " "	100	25	57	10	4575	1143¾
" " " "	100	50	58 7/10	5	4378	1094½
" " " "	100	75	60	7	4317	1079¼
" " " "	100	100	61½	6	3755	938¾
" " " "	100	125	62½	7	3505	876¼
" " " "	100	150	63 7/10	8	3341	835¼
" " " "	100	175	65	6	3523	880¾
Red Buttes plaster, no retarder	100	0	50	?	8945	2236¼
" " " " "	100	100	55	?	6622	1655½
Agatite plaster, market sample	100	0	50	?	3550	887½
" " " "	100	100	55	?	2597	649¼

TABLE 17.

ADHESIVE STRENGTH OF PLASTERS.

Material.	Adhesive Strength per Square Inch.		
	Kept in	7 Days.	28 Days.
Stucco, Ft. Dodge, Iowa	Air	87	133
" " " "	Water	87	75
Kallolite stucco, Ft. Dodge, Iowa	Air	45	115
" " " " "	Water	31	
" plaster, " " "	Air	52	102
" " " " "	Water	43	
Duncomb " " " "	Air	62	81
" " " " "	Water	..	84
Mineral City plaster, Ft. Dodge, Iowa	Air	72	212
" " " " " "	Water	..	84
Stone plaster, Ft. Dodge, Iowa	Air	31	80
Flint " " " "	"	64	114
" " " " "	Water	26	
Acme plaster, Acme, Texas	Air	76	103
Baker stucco, Kansas	"	..	117
" " "	Water	98	100
" plaster "	Air	83	105
" " "	Water	55	95
Plaster, Okarche, Oklahoma	Air	82	
" " "	Water	63	133

Rate of Set and Hardening.

A pure plaster of Paris will normally harden or set in from five to fifteen minutes after having been mixed with water. Plasters made from impure gypsum will be considerably slower setting than this, setting usually in from one to two hours.

When plasters are to be used for structural work, they must be either naturally slow-setting, like some of the cement plasters, or be made slow-setting by proper treatment. Retarders are therefore used at plaster-plants in preparing their product for the market. Occasionally, though rarely, a plaster will be naturally too slow setting for the particular use to which it is to be applied. In this case an accelerator must be used.

Theory of the action of retarders and accelerators.—As will be noted later, the materials most commonly used as retarders are glue, tankage, and other organic and uncrystallized materials, while accelerators are usually inorganic and crystallized This fact suggested a theory as to the cause of the action of accelerators and retarders. The theory, as set forth * by its originator, Dr. Grimsley, is as follows:

Dr. Grimsley assumes that the set of plaster is due to the presence of a few small crystals which have escaped dehydration during burning and which set the example, so to speak, to the other crystals to form; and, further, that the strength of the set material is due to the formation of a mass of interlacing crystals. The action of retarders and accelerators is therefore explained by assuming that " any substance (added to the water with which the calcined plaster is mixed, or to the dry plaster) which will keep the molecules apart or from too close contact will retard the setting. Such substances are dirt or organic matter that is not of a crystalline character." On the other hand, the action of accelerators is ascribed to the fact that, being of crystalline character, they induce crystallization in the plaster to which they are added.

It is probable that the researches of Rohland on the effect of various substances on the speed of hydration of plasters, Portland cement, etc., are directly applicable to the question on hand. In summing up his conclusions, Rohland decided that substances which increase the solubility of the cementing material accelerate its speed of hydration, while substances which decrease the solubility of the cementing material retard its hydration.

Materials used as retarders.—The materials used as retarders are usually of animal or vegetable origin. Glue, sawdust, blood, and pack-

* Vol. 5, Reports Geological Survey Kansas, pp. 167, 168.

ing-house tankage are some of the retarders most commonly used. Many "patent" retarders are also on the market, most of which are based on one or more of the organic materials noted above.

In the course of the experiments by Slosson and Moudy, recorded below, an effort was made to obtain a cheap and satisfactory home-grown retarder. With this in view a common western cactus (*Opuntia platycarpia*) was dried and ground. The common mallow (*Malvastrum coccineum*) was also prepared in a similar manner. The retarders thus made were light green in color, possessed no disagreeable odor, and when used in the proportion of 2 pounds of retarder to a ton of plaster gave excellent results. It is probable that many other plants, dried and ground in similar fashion, would form satisfactory retarders.

Effect of retarders on strength of plasters.—The following table * contains the results of compression tests by Profs. Slosson and Moudy on plasters containing various amounts of retarder. It appears to show conclusively that the compressive strength (and inferentially the tensile strength) of plasters decreases as the amount of retarder increases.

TABLE 18.

EFFECT OF RETARDERS ON STRENGTH OF PLASTERS.

	Pounds of Retarder per Ton of Plaster.	Crushing Strength in Pounds.	
		2-inch Cube.	Per Square Inch.
Laramie plaster.....	0	5345	1359
" "	2	4065	1016
Red Buttes plaster..	0	8945	2236
" " " ...	2	7192	1798
" " " ...	4	6480	1620

In making the tests the finely ground retarder was accurately weighed and thoroughly mixed with the dry plaster. Water was then added and the mixture, placed on a glass plate, was fashioned into a pat about 4 inches in diameter. For determining the setting time two needles were used, each $\frac{1}{12}$ inch in diameter, one loaded with a weight of $\frac{1}{4}$ lb., the other with a weight of 4 lbs. The time when the more lightly weighted needle ceased to make a decided impression on the surface of the plaster pat is reported as "initial set," and when the more heavily weighted needle was supported without indenting the plaster is reported as "final set."

* Tenth Ann. Rep. Wyoming Agric. and Mech. College.

TABLE 19.

EFFECT OF VARIOUS RETARDERS ON RATE OF SET.

Kind of Plaster.	Kind of Retarder.	Pounds Retarder per Ton.	Initial Set, Minutes	Final Set, Minutes	Remarks.
Laramie	None	0	145	225	
"	Market sample	?	280	335	
"	" "	?	...	720	
"	Wymore	1	320	330	
"	"	2	365	430	
"	"	4	520	655	
"	"	6	590	690	Cracked a little.
"	"	8	785	...	Never hardened.
"	Webster City	2	350	390	
"	" "	4	535	645	Cracked somewhat.
"	" "	6	735	...	Cracked badly.
"	" "	8	755	...	Did not set.
"	Swift's, Chicago	1	260	310	
"	" "	2	265	310	
"	" "	4	280	315	
"	" "	6	290	320	
"	Swift's, Kansas City	1	...	310	
"	" " "	2	215	250	
"	" " "	2	255	315	
"	" " "	4	250	315	
"	" " "	4	255	310	
"	" " "	6	250	300	
"	" " "	6	215	255	
"	Cactus	2	245	285	
"	"	2	275	320	
"	"	4	250	310	
"	"	6	290	340	
"	Malva	2	245	295	
"	"	4	280	295	
"	"	6	275	310	
"	Glucose	6	290	375	
"	Clay bentonite	6	240	320	
"	" "	10	260	330	
Red Buttes stucco	None	0	30	50	
" " "	"	0	24	42	
" " "	"	0	20	32	
" " "	Wymore	2	60	105	
" " "	"	8	270	...	Did not set.
Red Buttes plaster	None	0	50	80	
" " "	Wymore	2	285	345	
" " "	"	8	505	...	Soft-cracked.
" " "	Market sample	?	310	375	
Agatite plaster	" "	?	240	305	

Use of accelerators.—In making dental plaster and plaster for certain other purposes an extremely rapid set is desirable. For this purpose many crystalline salts are available, common salt being one of the best accelerators known.

TABLE 20.

EFFECT OF ACCELERATORS ON RATE OF SET.

Kind of Plaster.	Kind of Accelerator.	Pounds Accelerator per Ton.	Time of Set, in Minutes.	
			Initial Set.	Final Set.
Laramie	None	0	145	225
"	Common salt	6	55	150
"	Sodium sulphate	6	150	170
"	Sodium carbonate	6	145	170

References on properties and tests of plasters.—The following brief list covers the principal papers on this subject. (See also p. 62.)

Bailey, E. H. S. On the chemistry of gypsum, plaster of Paris, and cement plaster. Vol. 5, Reports Kansas Geological Survey, pp. 134–170.

Marston, A. Preliminary tests of stucco and plaster made by the Civil Engineering Department of Iowa State College. Vol. 12, Reports Iowa Geological Survey, pp. 224–235. 1902.

Slosson, E. E., and Moudy, R. B. The Laramie cement plaster. 10th Ann. Rep. Wyoming, College Agriculture and Mechanics. 1900.

Anon. Tests for plaster of Paris. Stone, vol. 25, pp. 331–334. 1903.

Hardening gypsum and plaster.—The following methods of hardening an ordinary plaster have been recently recommended:*

(1) Two to 4 per cent of finely ground marshmallow-root are intimately mixed with powdered plaster and the mixture kneaded to a dough with 40 per cent of water. The resulting mass resembles a stiff clay, hardens in about an hour, and finally becomes hard enough to cut, file, or bore. A harder and tougher mass may be obtained by increasing the quantity of marshmallow-root to 8 per cent. Gum, dextrin, or glue may be substituted for the marshmallow-root if more convenient. If the objects are to be exposed to high temperatures shellac may be used.

(2) Six parts of gypsum are mixed with one part of freshly slaked lime and the mixture is soaked with a concentrated solution of magnesium sulphate. In preparing this mixture, too much gypsum must not be poured into the water, and the mixture must be stirred quickly so that lumps do not form. The smaller the quantity of water used the thicker and firmer is the cement. The porosity caused by the gradual loss of water can be obviated by soaking the objects in a solution of ozocerite or wax in oil of turpentine, varnish, or hot tar, or by coating them with shellac.

* Journ. Soc. Chem. Industry, vol. 21, p. 347.

CHAPTER IV.

FLOORING-PLASTERS AND HARD-FINISH PLASTERS.

THE two groups of plasters to be considered in this chapter agree (1) in being prepared by burning gypsum at a higher temperature than is employed in the manufacture of plaster of Paris and "cement" plasters, and (2) in being products which, for plasters, set rather slowly but finally take on great hardness. Because of these last properties, the flooring-plasters and hard-finish plasters are available for certain uses to which ordinary plasters are ill adapted. So much for the resemblances between the two groups. Their points of difference are, that the flooring-plasters are prepared by simple burning at high temperatures, while the hard-finish plasters are produced by a *double* burning, with the additional use of chemicals.

Neither product is made to any extent in the United States, though a considerable quantity of hard-finish plasters are imported every year. The data obtainable as to processes of manufacture are scanty, and the descriptions published are often contradictory, so that it has been difficult to prepare a satisfactory account of these products. It is believed, however, that the descriptions given below contain no errors of importance.

Flooring-plasters.

The flooring-plasters ("Estrichgips" of German reports) include those plasters made by calcination of a relatively pure gypsum at temperatures of 400° F. or higher.

In the literature of gypsum and plaster it is often stated that gypsum, burned at temperatures exceeding 400° F., yields a completely dehydrated product—an artificial anhydrite—which is entirely valueless as a structural material, because it has completely lost its property of recombining with water. This statement is, however, erroneous, for plasters burned at such temperatures are regularly made and used. They set with extreme slowness, however, and require very fine grinding.

Composition of flooring-gypsum.—Until very recently no satisfactory discussion of this phenomenon had been attempted, and the few published accounts of this manufacturing processes employed were con-

tradictory as to temperatures reached and results attained. A paper published in 1903 by Van't Hoff gives the results of a very detailed series of experiments, which its author summarizes as follows:

"The essential result of the investigation, therefore, is that in the heating of gypsum after total dehydration, which occurs at about 190°, the capacity to bind water is at first retained, and is only gradually lost, either by more intense or by longer heating. The retention of the crystalline form, which is probably due to burning without previous division into small bits, checks this so-called dead-burning, and is therefore of technical importance. We found no evidence to support the statement that, after dead-burning, a new binding capacity appears at a high temperature, in which case even the natural anhydrite would be suitable for burning floor-gypsum."

Effects of high temperatures on resulting plasters.—In spite of the concluding observation in the last paragraph, there are definite proofs that such reappearance of setting properties does occur.

An actual series of experimental tests of the effects of temperature on the properties of the resulting plaster was carried out, as has earlier been noted, by MM. Leduc and Chenu. Some of these results have been presented on p. 39; those which give comparisons for the higher temperatures are now presented in the following table. All the samples were burned for a period of thirty minutes.

RESULTS OF GYPSUM BURNING AT HIGH TEMPERATURES.

Temperature of Burning, Centigrade.	Initial Set.	Final Set.	Compressive Strength, Kilograms per Square Centimeter.	
			24 Hours.	1 Week.
150 degrees C.....	40 minutes	95 minutes	18.2	18.0
200 "	20 "	60 "	59	54
250 "	10 "	26 "	92	90
300 "	4 "	12 "	72	110
350 "	2 "	11 "	47	96
400 "	2 "	65 "	25	84
450 "	1 minute	3 hrs., 51 min.	17	64
			4 Days.	1 Week.
500 degrees C.....	4½ minutes	4 days	10	28
550 "	4 hours	4 "	6	18
600 "	3 days	20 "		
900 "	9 "	Over 20 days		
			1 Week.	4 Weeks.
1100 degrees C.....	30 hours	.....	13	80
1200 "	20 "	.....	30	41
1300 "	36 "	.....	12	71

It will be seen that the setting and other properties, which decrease steadily after 250 to 400° are reached, seem to reappear at very high temperatures, from 1000° upward. But as yet no industrial use is made of this fact, for the German flooring-plasters seem to be burned at far lower temperatures, and to depend for their properties partly on the fact that the gypsum is not ground before burning.

Methods of manufacture.—Flooring-gypsum is, in any case, a pure plaster, entirely free from water. It is manufactured by burning pure gypsum, broken into lumps but not finely crushed, in a vertical kiln. The fuel, usually coal, is burned on a grate set at one side of the kiln, and the hot gases pass directly through the mass of gypsum, though neither fuel nor ashes come into direct contact with it. The temperature reached is, according to Wilder, about 500° C. The gypsum must not be exposed to this temperature for more than four hours, for a longer heating would deprive it entirely of its setting properties, as noted by Van't Hoff in the paper presented above.

Uses of flooring-gypsum.*—As its name denotes, flooring-gypsum (Estrichgips) is extensively used in Germany for floors, giving a very hard and durable surface. As the material attains this hardness only when it is protected from moisture during setting, care must be taken to give it a suitable foundation. If the material dries unevenly or very rapidly cracks will appear on its surface. In this case the floor should be covered with water until the surface is soft and the cracks closed, after which it is allowed to dry again. After standing about twelve hours and becoming fairly hard the floor is pounded with wooden mallets and smoothed with trowels.

Pure flooring-plaster gives the best results for hardness, but for economy it may be used in a mixture of two parts plaster to one part sand, ashes, etc. A cubic meter of hardened flooring-gypsum weighs about 2000 kg., equivalent to a weight of about 120 lbs. per cubic foot.

Flooring-plasters are manufactured on a fairly large scale in Germany, but have not been made or utilized in England or the United States. Under the next group (Hard-finishing Cements), however, will be found descriptions of a number of products which have been manufactured in these latter countries and which are very closely related to the dead-burned plasters. The only difference in technology between the two groups is that while the flooring-plasters are prepared from pure gypsum the hard-finishing cements are prepared from gypsum to which alum or some similar material has been added.

* The data on the uses of flooring-gypsum are largely taken from Wilder's paper, cited previously.

Hard-finish Plasters.

The materials grouped under this name include those plasters which owe their hardness and slow set not only to being burned at high temperatures, but to the fact that they have been treated with alum or other chemicals during manufacture. As thus defined, the hard-finish plasters include the various materials known commercially as " Keene's cement," " Parian cement," " Mack's cement," etc.

Keene's cement.—The most prominent representative of the group of hard-finishing cements is that known to the trade as Keene's cement. Originally manufactured under English patents which have now expired, the term " Keene's " is applied by various manufacturers to their product, in the same manner as the term " Portland " has become generalized. Large quantities of Keene's cement are annually imported, while its manufacture in the United States has been of late years successfully begun.

Keene's cement is sharply distinguished from the other members of the group of hydrate cements or " plasters," not only by the properties of the product, but by its method of manufacture. In its preparation a very pure gypsum is calcined at a red heat, the resulting dehydrated lime sulphate is immersed in a bath of alum solution and, after drying, is again burned at a high temperature. After this second burning the product is finely ground and is then ready for the market. This sketch of the process is a general outline of the methods used, and in the essentials is followed in all plants, though slightly modified at different plants according to the experience gained by each manufacturer.

The gypsum used should be as pure as possible, and especially it should be free from such impurities as might tend to discolor the product, which should be a pure white. Even the Virginia gypsum, which on analysis shows but a trace of iron oxide, is not entirely satisfactory; for on heating to the temperature necessary for the manufacture of Keene's cement, minute red streaks appear in the lumps of gypsum. The following analyses show the composition of gypsum from Virginia and Kansas, both of which have been used in the preparation of a domestic Keene's cement:

	Kansas.	Virginia.
Lime sulphate	77.46	99.58
Water	20.46	
Iron and aluminum oxides	0.10	0.036
Silica and insoluble	0.19	0.116
Magnesium carbonate	0.34	0.221
Lime carbonate	1.43	

It will be seen that both materials are very pure gypsums, and that there is no apparent reason why the Virginia material should not be as satisfactory as that from Kansas.

The calcination of the product is usually carried on in small vertical kilns closely resembling those which are in common use for lime-burning. These kilns are charged with alternating layers of fuel (usually coal) and lump gypsum. Small rotary kilns have been used experimentally, but have not proven successful, as the calcined product from a rotary kiln is discharged in small fragments which cannot be treated satisfactorily in the alum-bath. After burning to a red heat the gypsum is submitted to the action of a 10 per cent alum solution. It is then recalcined and finely ground in emery-mills.

The product is a very fine grained white powder. On the addition of water this cement hardens, but the hardening is slow relative to that of other plasters. Another peculiarity of the material is that even after the hardening has commenced, the partly set cement may be reworked with water and will take its set just as satisfactorily as if the process of hardening had not been interrupted.

An analysis of a Keene's cement manufactured in Kansas is given in " Tests of Metals, etc., at Watertown Arsenal, 1897," p. 403:

Silica (SiO_2)	tr.
Alumina (Al_2O_3)	tr.
Iron oxide (Fe_2O_3)	
Lime (CaO)	42.04
Magnesia (MgO)	tr.
Sulphur trioxide (SO_3)	56.54
Carbon dioxide (CO_2)	1.37

According to a circular issued by the sales-agent for one brand the following tests of two brands of Keene's cement were made by Lathbury and Spackman. The table below shows the tensile strength obtained, in pounds per square inch, at the end of seven days.

TABLE 21.

TENSILE STRENGTH OF KEENE'S CEMENT.

Maker.	Grade.		No. 1.	No. 2.
	Superfine.	Coarse.		
Improved Keene Cement Co., Long Island City, N. Y.	548 lbs.	606 lbs.	680 lbs.	693 lbs.
J. B. White & Bro., London, England.	405 "	511 "		

An American Keene's cement made in Kansas was tested in 1892 by O. S. Carll for tensile strength with the following results. The cement was mixed neat, with enough water to make a stiff plaster.

TABLE 22.

TENSILE STRENGTH OF KEENE'S CEMENT.

	24 Hours.	7 Days.
Specimen No. 1.....	374 lbs.	630 lbs.
" " 2.....	325 "	698 "
" " 3.....	402 "	678 "
Average.....	367 lbs.	669 lbs.

Mack's cement * consists of dehydrated gypsum (flooring-plaster) to which 0.4 per cent of calcined sodium sulphate (Na_2SO_4, Glauber's salts) or potassium sulphate (K_2SO_4) has been added. "This cement is unusually hard and durable, sets quickly and unites minutely with the material on which it is placed. It is used as a covering for wire mesh on walls and ceilings, as well as for floors, and may be mixed with sand or ashes. Its surface is but slightly porous and for this reason absorbs but little oil when covered with paint."

References on dead-burned and hard-finish plasters.

Eckel, E. C. Plasters and hard-finishing cements in the United States. Engineering News, vol. 49, pp. 107, 108. Jan. 20, 1903.

Grimsley, G. P. (Hard-finish plasters.) Vol. 5, Reports Kansas Geological Survey, pp. 115–118. 1899.

Redgrave, G. R. Calcareous cements. London, 1895. Pp. 196–199.

Rohland P. (Influence of catalysers on velocity of hydration of plasters, etc.) Zeitschrift anorganische Chemie, vol. 31, pp. 437–444. Abstract in Journ. Soc. Chem. Industry, vol. 21, p. 1233. 1901.

Van't Hoff and Just, G. Der hydraulische oder sogenante Estrichgips, Sitzungsberichte der Kgl. Preuss. Akad. der Wissenschaften, 1903, vol. 1. pp. 249–258.

Wilder, F. A. The gypsum industry of Germany. Vol. 12, Reports Iowa Geological Survey, pp. 192–223. 1902.

* Wilder, F. A. Gypsum Industry of Germany, p. 208, vol. 12, Reports Iowa Geol. Survey. 1902.

CHAPTER V.

THE PRODUCTION AND UTILIZATION OF GYPSUM.

THE world's production of gypsum amounts at present to around five million tons a year, of which slightly over 40 per cent is produced in the United States and slightly under 40 per cent in France. Canada with 10 per cent of the total and Great Britain with 6 per cent represent the next two countries in rank. Tonnages of far less importance are contributed by a number of countries all over the world.

In the present chapter an attempt will be made to utilize the available statistics regarding the gypsum and plaster industries so as to clear up some of the present uncertainties regarding vital points in these industries. For this purpose the questions of world output, and of production in the leading countries, will first be stated. After that is done it will be possible to go further, and see how these outputs are utilized in various forms of gypsum products and in various industries.

Total world's output of gypsum.—The following table contains the data available concerning the world's total output of gypsum during years just before the war. Though correct so far as the leading countries are concerned, there are undoubtedly many omissions of small producers; no reports being included from any of the Latin-American countries, for example; and the figures given for Germany seem to be very much too small. All are in short tons.

TABLE 23.

WORLD'S OUTPUT OF GYPSUM, 1910–1912.

Country.	1910.	1911.	1912.
United States	2,379,057	2,323,970	2,500,757
France	1,760,901	1,874,291	1,979,595
Canada	525,246	518,383	578,458
Great Britain	286,226	309,886	319,526
Germany	59,962	66,568	62,957
Algeria and Tunis	55,751	57,220	59,965
Australia	19,092	15,110	15,767
India	7,362	10,296	23,557
Cyprus	7,276	9,595	5,571
Greece	268	1,392	107
Total reported, short tons	5,101,141	5,186,711	5,546,260

From these data we may fairly assume that in a period of good business in the near future, the world output of gypsum is likely to run about six or seven million tons a year. With this in view, attention may be turned to the statistics relative to the three leading producers—United States, France, and Canada.

Gypsum Production of the United States.

The United States has been for many years past the largest gypsum producer in the world, a condition due not only to the advantages of an excellent market for gypsum products, but to the existence within its borders of very extensive gypsum deposits.

Geologic distribution of gypsum deposits.—Gypsum deposits have been formed at many periods of the earth's history, for the chief factor requisite for their formation is the existence of arid climatic conditions, causing the evaporation of extensive bodies of water. Such climatic conditions have appeared at different times in geologic history, and in each case we have as a result a series of gypsum deposits.

The more important gypsum-producing periods are, however, few in number when any particular area is taken into consideration. Throughout the entire United States, for example, the bulk of the workable gypsum deposits were formed during four periods.

(1) In the eastern United States a great period of salt and gypsum formation occurred in the Salina period of the Silurian. This gave rise to the gypsum deposits now worked in New York, Ohio and Ontario; as well as to some of those in Michigan, and to the deposits of the Winnipeg region of Manitoba.

(2) The next period of dry climates appears to have been early in the Carboniferous; for in the lower Carboniferous we find gypsum deposits in such widely scattered areas as Newfoundland, Nova Scotia, New Brunswick, Michigan, Virginia and in some of the western states.

(3) The third great gypsum period occurred during the Permian or Triassic deposition in the areas west of the Mississippi. In rocks of this age we find gypsum deposits in South Dakota, Iowa, Kansas, Oklahoma, Texas; as well as in some areas further west, and in Alaska.

(4) Still later, in the Tertiary of the west, gypsum deposits were extensively formed in all of the states and provinces lying west of the Missouri and Winnipeg drainages.

(5) Lastly, sporadic and local formations of gypsum materials have occurred in quite recent times, for the gypsum sands of new Mexico

and the gypsum earth deposits of Kansas are, in their present form, of very late origin.

Geographic distribution.—In dealing with a raw material so widely distributed by nature, it is difficult to adequately summarize the facts concerning its geographic distribution in the United States. Such a summary, however, will be of value as throwing light on some features connected with the manner in which the manufacture of gypsum products has become localized.

East of the Mississippi the United States has only three large and important areas containing gypsum deposits. Of these one is in central and western New York; the second in Michigan with a continuation in Ohio; and the third in southwestern Virginia.

Between the Mississippi and the Rockies the main gypsum deposits are those of Permian or Triassic age, which afford isolated deposits in South Dakota and Iowa, and then a series of almost continuous deposits through Kansas, Oklahoma and Texas. So far as reserve tonnage is concerned, this group is probably the most important in the United States.

West of the Rocky Mountains, the Tertiary basins carry important deposits of gypsum in widely scattered localities; and in the Pacific Coast states there are scattered deposits of different ages.

Sources of output by states.—The total gypsum of the United States now amounts to well over two million tons a year. Its chief sources are indicated when we consider the output classified by states, as in the table following:

TABLE 24.

GYPSUM OUTPUT BY STATES, 1918–1919, SHORT TONS.

	1918. Tons.	1919. Tons.‡
New York	531,038	591,153
Iowa	327,927	421,279
Michigan	286,768	339,125
Ohio	199,456	251,259
Texas	157,388	176,607
Oklahoma	126,208	114,313
Nevada	*	91,756
Kansas	54,958	78,479
Wyoming	41,877	51,079
All others	331,395	305,113
Total U. S	2,057,015	2,420,163

The total output came in each year from 57 companies, located in 19 states, which gives a fair idea of the dispersion of the industry,

and the extent of its possible sources of supply. Yet it will also be noted that, out of the 19 states which did mine gypsum only a few were of real importance in the industry. Two-thirds of the entire American output is produced by the four states of New York, Iowa, Michigan and Ohio.

To this domestic supply the United States adds, chiefly by imports from Canada. This matter, and the ways in which both domestic and imported product are utilized, will be taken up later (page 87). Here we can turn to consideration of the French and Canadian gypsum deposits and output.

Gypsum Deposits of France.

As the gypsum deposits of France rank closely to those of the United States as producers, their competitive importance justifies a brief description. Two main areas supply the bulk of the French gypsum output. One of these, and by far the more important, lies in the Paris basin. The second in rank is in southeastern France.

The gypsum-bearing series which furnishes by far the greater part of the French output falls in the Ludien stage of the Oligocene Tertiary. It is made up, in its typical areas, of a heavy series of alternating beds of gypsum and clays. Four gypsum beds or zones are traceable in the region of Paris, where the series is best developed; the lowermost gypsum bed is thin and irregular, but the total thickness of workable gypsum in the other three beds ranges from 30 to over 85 feet. Of these three beds the topmost is the thickest and in every way most important; it ranges in thickness, at various points in the Paris region, as follows:

Montmartre	70 feet
Argenteuil	50 "
Villejuif	13 "
Bagneux	10 "

In 1902 the three departments of Seine, Seine-et-Oise, and Seine-et-Marne produced over one million metric tons of gypsum from this series, and chiefly from the topmost bed just noted. It is developed in open cuts, by galleries following in from the outcrops, and by shafts —according to the location of the workings with respect to the adjoining topography.

A series of typical analyses of French gypsums, taken from the work of Leduc and Chenu (cited on page 62) is given here in Table 25.

TABLE 25.

ANALYSES OF FRENCH GYPSUMS.

	(1)	(2)	(3)	(4)	(5)
Silica	0.65	0.85	0.35	0.40	0.80
Iron and alumina	0.25	0.65	0.60	0.60	0.60
Lime	32.85	32.20	32.40	32.80	32.10
Sulphur trioxide	45.60	45.30	45.60	45.50	45.40
Water	20.75	20.35	20.30	20.60	20.40
Carbon dioxide	.....	0.30	0.60	.....	0.20
Loss, etc	.....	0.40	0.15	0.40	0.50

	(6)	(7)	(8)	(9)	(10)
Silica, iron and alumina	0.05	0.10	0.22	0.18	0.57
Lime	32.61	32.70	32.88	32.92	32.80
Sulphur trioxide	46.38	46.32	45.97	46.12	45.66
Water	20.83	20.86	20.60	20.72	20.18
Loss, etc	0.13	0.02	0.28	0.06	0.18

Analyses 1–5 from points in the Paris Basin; analyses 6–10 from points in department of Alpes Maritimes, in southeastern France.

1. Argenteuil.
2. Gagny.
3. Fontenay-s-Bois.
4. Cormeilles.
5. Villemomble.
6, 7. Daluis.
8, 9. Lantosque.
10. La Clave.

Gypsum Production of Canada.

We are especially interested, from a trade standpoint, in the gypsum output and utilization of the Dominion of Canada, for much of the output reaches our own plaster and cement industries. Data on Canadian output over a series of years are in the table following:

TABLE 26.

CANADIAN SALES OF GYPSUM AND GYPSUM PRODUCTS, 1886–1913.

Calendar Year.	Tons.	Value.	Per Ton.	Calendar Year.	Tons.	Value.	Per Ton.
		$	$ cts.			$	$ cts.
1886	162,000	178,742	1 10	1900	252,101	259,009	1 02
1887	154,008	157,277	1 02	1901	293,799	340,148	1 16
1888	175,887	179,393	1 01	1902	333,599	379,479	1 14
1889	213,273	205,108	0 96	1903	314,489	388,459	1 24
1890	226,509	194,033	0 86	1904	345,961	373,474	1 08
1891	203,605	206,251	1 01	1905	442,158	586,168	1 32
1892	241,048	241,127	1 00	1906	469,022	643,294	1 37
1893	192,568	196,150	1 02	1907	485,921	646,914	1 33
1894	223,631	202,031	0 90	1908	340,964	575,701	1 69
1895	226,178	202,608	0 89	1909	473,129	809,632	1 71
1896	207,032	178,061	0 86	1910	525,246	934,446	1 78
1897	239,691	244,531	1 02	1911	518,383	993,394	1 92
1898	219,256	232,515	1 06	1912	578,458	1,324,620	2 29
1899	244,566	257,329	1 05				

The marketed output of the different Canadian provinces, over a series of years, is given in Table 27 following. It will be noted that Nova Scotia has always ranked first by a large margin; and that New Brunswick has ranked second, though its position is now threatened by the recent rapid growth in the output of Ontario and Manitoba.

TABLE 27.

PRODUCTION OF GYPSUM AND GYPSUM PRODUCTS, BY PROVINCES, 1887–1913.

Calendar Year.	Nova Scotia.		New Brunswick		Ontario.		Manitoba.		British Columbia.	
	Tons.	Value.	Tons.	Value.	Tons.	Value.	Tons.	Value.	Tons.	Value
		$		$		$		$		$
1887	116,346	116,346	29,102	29,216	8,560	11,715				
1888	124,818	120,429	44,369	48,764	6,700	10,200				
1889	165,025	142,850	40,866	49,130	7,382	13,128				
1890	181,285	154,972	39,024	30,986	6,200	8,075				
1891	161,934	153,955	36,011	33,996	5,660	18,300				
1892	197,019	170,021	39,709	65,707	4,320	5,399				
1893	152,754	144,111	36,916	41,846	2,898	10,193				
1894	168,300	147,644	52,962	48,200	2,369	6,187				
1895	156,809	133,929	66,949	63,839	2,420	4,840				
1896	136,590	111,251	67,137	59,024	3,305	7,786				
1897	155,572	121,754	82,658	118,116	1,461	4,661				
1898	132,086	106,610	86,083	121,704	1,087	4,201				
1899	126,754	102,055	116,792	151,296	1,020	3,978				
1900	138,712	108,828	112,294	145,850	1,095	4,331				
1901	170,100	136,947	121,595	189,709	1,504	5,692	600	7,800		
1902	206,087	181,425	124,041	170,153	1,917	7,699	1,554	20,202		
1903	189,427	173,881	119,182	172,080	2,720	21,988	3,160	20,510		
1904	218,580	153,600	190,991	187,524	2,930	18,350	4,000	14,000		
1905	272,252	298,248	163,553	232,586	1,853	23,834	4,500	31,500		
1906	333,312	345,414	131,246	250,960	2,965	24,420	3,200	22,500		
1907	357,411	380,859	118,106	213,638	10,404	52,417				
1908	234,455	230,433	81,620	191,312	10,389	42,456	14,500	111,500		
1909	345,682	364,379	98,716	226,975	11,731	48,278	17,000	170,000		
1910	400,455	458,638	90,236	213,579	15,055	67,229	19,500	195,000		
1911	353,999	406,457	93,205	115,044	27,399	98,018	43,000	372,000	780	1875
1912	376,082	481,493	82,757	185,821	53,119	176,056	66,500	481,250		

Analyses of Canadian gypsums.—In view of the close trade relations between the two countries, the analyses of a large series of Canadian gypsums are presented in Table 28, following. These have been selected from a very large number given in the works of Cole and Jennison, previously cited.

TABLE 28.

ANALYSES OF CANADIAN GYPSUMS.

No.	Silica.	Alumina and iron oxide.	Lime (CaO).	Sulphur Trioxide.	Combined Water.
1	0.40	0.60	32.92	46.36	19.55
2	0.80	1.80	32.72	45.24	20.17
3	0.06	0.10	32.40	46.12	20.40
4	0.46	0.03	32.16	46.27	20.75
5	1.18	9.80	28.95	41.06	18.45
6	8.86	2.72	27.92	38.21	17.80
7	....	0.58	32.95	44.03	20.00
8	....	0.16	32.23	46.56	20.80
9	0.12	0.50	32.86	45.86	20.47
10	1.72	0.74	33.25	42.76	19.30
11	0.32	0.20	32.42	46.12	20.60
12	0.14	0.86	32.62	46.06	20.30
13	2.32	0.26	31.41	45.15	20.20
14	0.07	....	33.10	45.95	20.85
15	0.15	....	32.97	46.16	21.00
16	0.90	0.20	32.20	46.00	20.60
17	0.50	....	32.24	46.08	20.85
18	....	....	32.34	47.36	20.90
19	0.06	....	32.70	46.88	20.66
20	0.20	....	32.49	47.24	20.75
21	2.12	0.20	36.76	36.11	16.27
22	2.40	0.30	32.40	39.31	17.69

1, 2. Hillsborough, Albert County, New Brunswick.
3. Hammond River, Kings County, N. B.
4. Sussex Valley, Westmoreland County, N. B.
5, 6. Plaster Rock, Victoria County, N. B. (used in Portland cement).
7. Parrsboro, Cumberland County, Nova Scotia.
8. Nappan, Cumberland County, Nova Scotia.
9. Philip River, Cumberland County Nova Scotia.
10. Pugwash, Cumberland County, Nova Scotia.
11. Wentworth, Hants County, Nova Scotia.
12. Threemile Plains, Hants County, Nova Scotia.
13. Windsor, Hants County, Nova Scotia.
14. East Bay, Cape Breton County, Nova Scotia.
15. Aspy Bay, Victoria County, Nova Scotia.
16. Inverness, Inverness County, Nova Scotia.
17. Boularderie Island, Victoria County, Nova Scotia.
18, 19, 20. Crown Gypsum Co., York, Ontario.
21, 22. Carson mine, York, Ontario. Shipped for use in Portland Cement.

The Uses of Gypsum.

Gypsum may be applied to a number of utilizations, dependent upon its physical and chemical properties. One series of uses arises from the facts that crude gypsum is a soft material, and the purer types are very white when ground. Another series is due to the chemical properties of crude gypsum, making it of use as a fertilizer and in the Portland cement industry. A third, and the most important group of uses is due to the fact that after calcining gypsum will set very hard on being mixed with water. Since all of these utilizations are of commercial importance, they may be separately discussed to advantage at the present stage of the study.

For the sake of clearness, the uses may be tabulated at the outset as follows:

A. Uses for crude gypsum, in which the physical characteristics of gypsum are the chief factors. **Pigment, filler and adulterant in various industries.**

B. Uses for crude gypsum in which the chemical characteristics of gypsum are the chief factors. **Land fertilizer; retarder for Portland cement.**

C. Uses for calcined gypsum, in which the setting properties of the calcined product are the chief factors. **Wall plasters, dental plasters, etc.**

The main uses of gypsum and its products will now be taken up separately, though attention will be directed principally toward the uses for crude gypsum, since the calcined products have received more detailed treatment in earlier chapters.

Paint uses.—Finely ground unburned gypsum enters into the paint trade in several ways. It is a convenient white filler or adulterant, as the case may be, for the lighter colored pigments; and on the other hand it is the base used in the manufacture of the better grade of imported Venetian red pigments. For this last purpose gypsum is used in proportions as high as five parts gypsum to one part iron oxide.

Fertilizer; land plaster.—From time immemorial crude gypsum has been used extensively as a fertilizer. In this use it appears to act much like ground limestone or lime. Since the introduction of high-grade potash salts from the German deposits the use of gypsum and lime has fallen off markedly; but in the past few years there has been a great renewal of interest in the subject of lime fertilizers, and it is possible enough that land plaster (ground crude gypsum) will also return to favor.

Retarder for Portland cement.—In later chapters of this volume (p. 474) this particular use of crude gypsum will be discussed in some detail, in connection with the manufacture of Portland cement. Here it is only necessary to say that a very large tonnage of gypsum is annually used for this purpose.

Calcined products.—The utilizations which have been noted all relate to the use of crude or unburned gypsum, though in almost every case a burned product could be used for the same purposes though at greater expense. But the main use of gypsum is in calcined or burned form. When so calcined, it is serviceable in the forms of plaster of Paris, wall plaster, etc., not only in structural work, but for a number of minor uses. Among these minor uses may be noted the bedding of plate glass for grinding, the making of pottery molds, dental plasters,

etc. It will not be necessary to discuss these products here, since several earlier chapters of this volume are devoted to consideration of their manufacture and properties.

Statistics of Utilization.

In a previous section of this chapter statistics were presented covering the production of gypsum throughout the world, with special reference to the output of the United States and Canada. Now, having seen to what general classes of utilization this total may be applied, it will be of interest to take up consideration of the statistics relative to the different uses to which the gypsum output of the United States is put.

The structure of the industries.—Before presentation of the statistics relative to the American and Canadian gypsum and plaster industries, it will be well to briefly summarize the principal facts regarding the structure of those industries, for otherwise the statistics would simply involve the reader in hopeless confusion.

The gypsum and plaster used in the United States are, for the most part, produced from American gypsum deposits; but a notable portion of the total is imported. During 1913, for example, of the total consumption amounting to about three million tons, about 2600 thousand tons were from domestic sources, and somewhat over half a million tons from foreign deposits.

The domestic gypsum supply is furnished by a large number of mines and quarries, scattered over many states. In 1913, for example, 82 American mines and quarries furnished to total domestic supply; and these were located in 18 different states and in Alaska.

Confining attention for the moment to the domestic supply, we can say that the gypsum mined may be sold in its crude form or it may be calcined before selling. If sold crude, it is almost invariably ground more or less finely; and the product is chiefly used either for fertilizer (" land plaster ") or in the Portland cement industry (see page 474). If calcined, it may either be prepared for final use at the original mill, or it may be shipped for some distance and receive its retarders, fiber, etc. at a " mixing plant." The American statistics presented in this chapter relate entirely to the gypsum and plaster at their first point of sale; and this fact must be borne in mind when these figures are considered.

Turning now to the imported portion of the gypsum and plaster supply, we may note that, owing to tariff conditions, it is imported chiefly in the form of crude gypsum, though a small tonnage of high-grade plasters are annually brought in. The gypsum imported comes almost entirely from New Brunswick and Nova Scotia; and enters chiefly at north Atlantic ports. We have no figures available covering

the final use of this imported gypsum. As a matter of fact we do know that the bulk of it is burned into plaster, mostly at New York harbor points; while some of it is used at American Portland cement plants.

TABLE 29.

CONSUMPTION OF GYPSUM IN THE UNITED STATES.

Year.	Produced in U. S., Short Tons.	Imported into U. S. Short Tons.	Total Tonnage Used, Short Tons.
1900	594,462	212,990	807,452
1901	633,791	238,310	872,101
1902	816,478	309,014	1,125,492
1903	1,041,704	269,484	1,311,188
1904	940,917	297,516	1,238,433
1905	1,043,202	403,119	1,446,321
1906	1,540,585	440,586	1,981,171
1907	1,751,748	455,890	2,207,638
1908	1,721,829	302,047	2,023,876
1909	2,252,785	353,597	2,606,382
1910	2,379,057	417,735	2,796,792
1911	2,323,970	390,262	2,714,232
1912	2,500,757	416,399	2,917,156
1913	2,599,508	451,925	3,051,433
1914	.....	.....	.....
1915	.....	.....	.....

Canadian gypsum production.—Table 27 gives the total tonnage of crude gypsum mined in Canada during a series of recent years.

Utilization of United States gypsum output.—The data contained in the annual volumes on Mineral Resources of the United States, published by the U. S. Geological Survey, are of service in arriving at conclusions on this important point. Taking two typical recent years, and disregarding small quantities disposed of in undeterminable ways, the results are as follows:

TABLE 30.

UTILIZATIONS OF UNITED STATES GYPSUM OUTPUT.

	1915.		1919.	
	Short Tons.	Average Price.	Short Tons.	Average Price.
		$		$
Crude; for Portland cement.....	406,393	1.30	470,267	2.83
for land plaster.....	69,256	1.77	39,978	4.64
Calcined; wall plaster, etc.....	1,520,308	3.80	1,393,141	8.48
glass factories.....	11,861	2.25	14,677	6.58
plaster board, etc.....	81,017	1.73	188,202	12.24

The fantastic effects of war on prices are of course visible in the last year of the table, but notwithstanding that the divisions made are of service.

Salt Lake City
Denver
Albuquerque
El Paso
Los Angeles
San Diego
Phoenix
Tucson
Las Vegas
Reno
Sacramento
San Francisco
Portland
Seattle
Spokane
Boise
Billings
Cheyenne
Pueblo
Colorado Springs
Santa Fe
Amarillo
Lubbock
Abilene
Dallas
Fort Worth
Austin
San Antonio
Houston
Oklahoma City
Tulsa
Wichita
Kansas City
Omaha
Minneapolis
Fargo
Bismarck
Rapid City
Sioux Falls
Des Moines
St. Louis
Memphis
Little Rock
New Orleans
Jackson
Birmingham
Atlanta
Nashville
Louisville
Cincinnati
Columbus
Indianapolis
Chicago
Milwaukee
Detroit
Toledo
Cleveland
Buffalo
Pittsburgh
Philadelphia
New York
Boston
Providence
Hartford
Albany
Syracuse
Rochester
Richmond
Norfolk
Charleston
Savannah
Jacksonville
Tampa
Miami
Orlando
Raleigh
Charlotte
Columbia
Knoxville
Chattanooga
Evansville
Peoria
Springfield
Quincy
Davenport
Cedar Rapids
Iowa City
Lincoln
Grand Island
North Platte
Scottsbluff
Casper
Cheyenne
Laramie
Rock Springs
Green River
Vernal
Grand Junction
Durango
Farmington
Gallup
Flagstaff
Yuma
Barstow
Bakersfield
Fresno
Stockton
Modesto
Eureka
Redding
Medford
Eugene
Salem
Olympia
Tacoma
Everett
Bellingham
Wenatchee
Yakima
Pasco
Walla Walla
Lewiston
Coeur d'Alene
Missoula
Great Falls
Helena
Butte
Bozeman
Miles City
Glendive
Williston
Minot
Grand Forks
Devils Lake
Jamestown
Aberdeen
Watertown
Huron
Pierre
Mitchell
Yankton
Norfolk
Hastings
Kearney
Grand Island
Columbus
Fremont
Omaha
Council Bluffs
Sioux City
Waterloo
Cedar Falls
Mason City
Fort Dodge
Ames
Iowa City
Davenport
Rock Island
Moline
Peoria
Bloomington
Springfield
Decatur
Champaign
Danville
Terre Haute
Lafayette
Muncie
Anderson
Kokomo
Fort Wayne
South Bend
Gary
Hammond
Michigan City
Elkhart
Goshen
Warsaw
Plymouth
Rochester
Logansport
Peru
Marion
Huntington
Wabash
Bluffton
Portland
Decatur
Fort Wayne
Angola
Auburn
Kendallville
Ligonier
Albion
Columbia City
Wabash
North Manchester
Huntington
Warren
Bluffton
Portland
Decatur
Berne
Monroeville
New Haven
Fort Wayne
Waynedale
Leo
Woodburn
Harlan
Churubusco
Columbia City
Larwill
Milford Junction
Syracuse
Wawaka
Kendallville
Ligonier
Albion
Rome City
Wolcottville
Lagrange
Howe
Topeka
Shipshewana
Middlebury
Goshen
Nappanee
Wakarusa
Bristol
Elkhart
Osceola
Mishawaka
South Bend
Granger
Walkerton
Plymouth
Argos
Culver
Knox
North Judson
Hamlet
Winamac
Monterey
Star City
Francesville
Rensselaer
Remington
Wheatfield
Kentland
Morocco
Goodland
Brook
Mount Ayr
Rensselaer
Fowler
Oxford

FIG. 22.

[To face p. 91.

PART II. LIMES.

CHAPTER VI.

COMPOSITION, ORIGIN, AND GENERAL CHARACTERS OF LIMESTONES.

LIMESTONE is the raw material on which is based the manufacture of lime, and it is also the most important ingredient, in one form or another, in a Portland-cement mixture. Further, impure limestones of certain types are employed in the manufacture of hydraulic limes and natural cements. It will thus be seen that limestone plays a very important part in the manufacture of nearly all the cementing materials discussed in this volume, only the plasters (Chapters I–V) being manufactured without its use.

For this reason it has seemed desirable to discuss in the present chapter the origin, composition, varieties, and chemical and physical characters of limestone in general. This has been done in considerable detail. The present chapter will therefore serve as an introduction, not only to the limes but to the hydraulic limes and the natural and Portland cements. More detailed statements concerning the special kinds of limestone required in the different industries will be found in the sections on those industries, particularly in Chapters XXI–XXIII of the section on Portland cement.

Origin of limestones.*—Limestones have been formed largely by the accumulation at the sea-bottom of the calcareous remains of such organisms as the foraminifera, corals, and mollusks. Many of the thick and extensive limestone deposits of the United States were probably deep-sea deposits formed in this way. Some of these limestones still show the fossils of which they were formed, but in others all trace of organic origin has been destroyed by the fine grinding to which the

* For a more detailed discussion of this subject the reader will do well to consult Chapter VIII of Prof. J. F. Kemp's "Handbook of Rocks."

shells and corals were subjected before their deposition at the sea-bottom. It is probable also that part of the calcium carbonate of these limestones was a purely chemical deposit from solution, cementing the shell fragments together.

A far less extensive class of limestones, though very important in the present connection, owe their origin to the indirect action of organisms. The "marks," so important to-day as Portland-cement materials, fall in this class. As the class is of limited extent, however, its method of origin may be dismissed here, but will be described later in the chapter on marls, Chapter XXIII.

Deposition from solution by purely chemical means has undoubtedly given rise to numerous important limestone deposits. When this deposition took place in caverns or in the open air it gave rise to onyx deposits and to the "travertine marls" of certain Ohio and other localities; when it took place in isolated portions of the sea through the evaporation of the sea-water it gave rise to the limestone beds which so frequently accompany deposits of salt and gypsum.

Varieties of limestone.—A number of terms are in general use for the different varieties of limestone, based upon differences of origin, texture, composition, etc. The more important of these terms will be briefly defined.

The *marbles* are limestones which, through the action of heat and pressure, have become more or less distinctly crystalline. The term *marl* as at present used in cement manufacture is applied to a loosely cemented mass of lime carbonate formed in lake basins as described in more detail in Chapter XXIII. *Calcareous tufa travertine* are more or less compact limestones deposited by spring or stream waters along their courses. *Oolitic* limestones, so called because of their resemblance to a mass of fish-roe, are made up of small rounded grains of lime carbonate. *Chalk* is a fine-grained limestone composed of finely comminuted shells, particularly those of the foraminifera. The presence of much silica gives rise to a *siliceous* or *cherty* limestone. If the silica present is in combination with alumina, the resulting limestone will be *clayey* or *argillaceous*.

Chemical composition of limestone.—A theoretically pure limestone is merely a massive form of the mineral calcite. Such an ideal limestone would therefore consist entirely of calcium carbonate or carbonate of lime, with the formula $CaCO_3[CaO+CO_2]$, corresponding to the composition calcium oxide (CaO) 56 per cent, carbon dioxide or carbonic acid (CO_2) 44 per cent.

As might be expected, the limestones we have to deal with in practice

depart more or less widely from this theoretical composition. These departures from ideal purity may take place along either of two lines:

a. The presence of magnesia in place of part of the line;

b. The presence of silica, iron, alumina, alkalies, or other impurities.

It seems advisable to discriminate between these two cases, even though a given sample of limestone may fall under both heads, and they will therefore be discussed separately.

The presence of magnesia in place of part of the lime.—A theoretically pure limestone would, as above noted, consist entirely of the mineral calcite or calcium carbonate; and would therefore correspond to the formula $CaCO_3$. Setting aside for the moment the possible presence of such impurities as iron, alumina, silica, etc., it may be said that lime is rarely the only base in a limestone. During or after the formation of the rock a certain percentage of magnesia is often introduced, thus giving a more or less magnesian limestone. In such mixtures part of the calcium carbonate is replaced by magnesium carbonate, so that a general formula for a mixture of this type would be:

$$x\mathrm{Ca}\cdot\mathrm{CO_3}+y\mathrm{Mg}\cdot\mathrm{CO_3}.$$

In this formula x might theoretically vary from 100 per cent to zero, while y might vary inversely from zero to 100 per cent. But as a matter of fact, this perfect gradation from a pure calcium carbonate to a pure magnesium carbonate does not occur in nature. There are wide gaps in the series, due to the formation, and intermixture, of certain definite minerals. The three minerals which enter into the problem are respectively:

$$\begin{aligned}\text{Calcite} &= \mathrm{CaCO_3}\\ \text{Dolomite} &= \mathrm{CaCO_3,\ MgCO_3}\\ \text{Magnesite} &= \mathrm{MgCO_3}.\end{aligned}$$

During past geologic periods the processes and conditions which permitted the formation of magnesite in any economic quantities at any given point, were very rare. On the other hand there were numerous opportunities for the formation of calcite, of dolomite, and of certain calcite-dolomite intermixtures. When we speak of limestones we limit the term to that portion of the series which lies between the limits of calcite on the one hand and dolomite on the other. The general formula for an actual limestone is therefore

$$x\mathrm{CaCO_3}+y\mathrm{CaCO_3,MgCO_3}$$

in which y and x vary inversely, from zero to 100 per cent.

Though magnesia is often described as an " impurity " in limestone, this term, as can be seen from the preceding statements, hardly expresses the facts in the case. The magnesium carbonate present, whatever its amount, simply serves to replace an equivalent amount of calcium carbonate, and the resulting rock, whether little or much magnesia is present, is still a pure carbonate rock. With the impurities to be discussed in later paragraphs, however, this is not the case. Silica, alumina, iron, sulphur, alkalies, etc., when present are actual impurities, not merely chemical replacements of part of the calcium carbonate.

The presence of silica, alumina, iron, and other impurities.—If a number of limestone analyses be examined, it will be found that the principal impurities present are silica, alumina, iron oxide, sulphur, and alkalies.

Silica when present in a marble or crystalline limestone is usually combined with alumina, iron, lime, or magnesia, and occurs therefore in the form of a silicate mineral. In an ordinary limestone it is very often present as masses or nodules of chert or flint, or else combined with alumina as clayey matter. In the softer limestones, such as the chalks and marls, the silica may be present as grains of sand.

Alumina is commonly present combined with silica either as grains of a silicate mineral or as clayey matter.

Iron may be present as carbonate, as oxide, or in the sulphide form as the mineral pyrite.

Sulphur is commonly present in small percentages in one of two forms: as pyrite or iron disulphide (FeS_2) or as gypsum or lime sulphate ($CaSO_4+2H_2O$).

The alkalies soda and potash are frequently present in small quantity, probably in the form of complex silicates.

Geologic and geographic distribution of limestones.—Limestones occur in every state and territory in the United States, though of course some states (Delaware, North Dakota, Louisiana, etc.) are so poorly supplied that they can never become important lime producers, while other states are almost entirely underlain by limestone strata. Geologically, the limestone utilized in various parts of the United States ranges entirely through the geological column, from the pre-Cambrian to the Pleistocene, inclusive.

Under such conditions of wide geographic and geologic distribution it is not practicable to give a summary of any value in the present volume. The list of references given in the following pages will enable the reader to ascertain the facts regarding the limestones of any given region in which he may be interested.

Burchard, E. F. Stone resources east of the Mississippi River. Mineral Resources U. S. for 1911, vol. 2, pp. 732–831. 1912.

Burchard, E. F. Stone resources in Great Plains and Rocky Mountain States. Mineral Resources U. S. for 1912, vol. 2, pp. 754–815. 1913.

Burchard, E. F., and others. Stone resources in the states west of the Rocky Mountains. Mineral Resources U. S. for 1913, vol. 2, pp. 1335–1408. 1914.

Eckel, E. C., and Burchard, E. F. Portland Cement Materials of the United States. Bulletin 522, U. S. Geol. Survey, 401 pp. 1913.

Miller, W. G. The limestones of Ontario. Ann. Rep. Ontario Bureau of Mines for 1904, pt. II, 143 pp. 1904.

Howe, J. A. The Geology of Building Stones. 455 pp. London, 1910. This is the best guide for commencing work on European limestones, and is, of course, specially good on British stones.

The volumes above listed include bibliographies which will give such further data in regard to special areas as may be needed.

Shells as sources of lime.—Most molluscan shells consist essentially of lime carbonate, with commonly very small percentages (less than 1 per cent) of magnesium carbonate, and traces of alkalies, phosphoric acid, etc. The analyses given in Table 31 will serve to illustrate the composition of the shells of three common species of molluscs.

These analyses show that in ordinary practice commercial lots of oyster-shell may be expected to carry around 5 per cent of silica, iron oxide and alumina; with entirely unimportant percentages of sulphur, potash, phosphorus, etc. It is probable that the clay impurities mentioned as being present in some quantity are in large part external impurities, and that they may vary in amount according to the condition and cleanness of the shell as secured.

TABLE 31.

ANALYSES OF VARIOUS MOLLUSCAN SHELLS.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	3.30	1.49	n. d.	0.20	0.16	n. d.
Alumina (Al_2O_3)	0.08					
Iron oxide (Fe_2O_3)	0.17	0.04	n. d.	0.04		
Lime (CaO)	52.14	53.37	n. d.	52.86	54.55	54.38
Magnesia (MgO)	0.25					
Alkalies (K_2O, Na_2O)	0.35					
Sulphur trioxide (SO_3)	0.16	0.81	0.80	0.35	0.28	0.28
Phosphorus pentoxide (P_2O_5)	n. d.	0.11	n. d.	0.05	0.001	n. d.
Carbon dioxide (CO_2)	41.61	40.60	n. d.	41.02	42.82	n. d.
Water						
Organic matter	2.32	3.48	3.17	5.02	2.01	2.04

1. Oyster-shell. L. P. Brown and J. S. H. Koiner, analysts. Amer. Chemical Journal, vol. 11, pp. 36–37.
2–3. Oyster-shell. How, analyst. Amer. Journal of Science, 2d series, vol. 41, p. 380.
4. Mussel-shell. " " " " " " 2d " " 41, p. 380.
5–6. Periwinkle-shell. " " " " " " 2d " " 41, p. 379–381.

At various point where the oyster-canning industry is largely developed oyster-shells are burned into lime. An important lime-burning industry is, for example, based upon the use of waste oyster-shells at Baltimore, Md. In the case of the lime whose analysis is given below the shells had been charged, mixed with small anthracite, into a cylindrical kiln, and the resulting lime consequently shows the presence of a considerable amount of coal-ash. By burning the shells in kilns with separate furnaces this can be avoided, giving a much improved product.

The following analyses were made * by L. P. Brown and J. S. H. Koiner on the oyster-shell used in lime-burning at Baltimore, Md., and the resulting lime:

TABLE 32.

ANALYSES OF OYSTER-SHELLS AND OYSTER-SHELL LIME.

	Shell.	Lime.
Silica (SiO_2)	3.30	6.29
Alumina (Al_2O_3)	0.08	0.42
Iron oxide (Fe_2O_3)	0.17	0.33
Lime (CaO)	52.14	85.49
Magnesia (MgO)	0.25	0.31
Alkalies (K_2O, Na_2O)	0.35	0.80
Sulphur trioxide (SO_3)	0.16	0.66
Carbon dioxide (CO_2)	41.61	0.70
Water	.....	3.97
Organic matter	2.32	

* American Chemical Journal, vol. 11, p. 37, 1889.

CHAPTER VII.

LIME-BURNING.

BEFORE taking up the discussion of manufacturing methods it will be of value to consider briefly the chemical principles upon which these methods are based and the classes of products which result.

The burning of a pure non-magnesian limestone.—An absolutely pure limestone, free from both magnesia and other impurities, corresponds in composition to calcium carbonate ($CaCO_3$). If a pure limestone be heated to 800° C. or over, this carbonate is dissociated, the carbon dioxide (CO_2) being driven off as a gas, while the calcium oxide (CaO) is left behind as a white solid, known as quicklime or caustic lime. This decarbonation may be expressed in a formula as follows:

Limestone ($CaCO_3$) + heat = CaO (lime) + CO_2 (carbon dioxide).

As the original lime carbonate consisted of 56 parts by weight of CaO to 44 parts of CO_2, the formula may be given a commercial quantitative value, as below:

100 lbs. limestone + heat = 56 lbs. quicklime + 44 lbs. carbon dioxide.

In the process of burning from limestone to quicklime, the material has therefore lost 44 per cent in weight. It has also decreased in bulk, but in a much smaller ratio, the decrease varying from 12 to 20 per cent. Pure limestone has a specific gravity of 2.715, while the true specific gravity of pure quicklime is 3.09 to 3.15, though much less in lumps.

The dissociation of limestone on heating begins at a temperature of about 750° C., but is usually not complete until 900° C. or thereabouts is reached. As the expulsion of the carbon dioxide is hindered by the presence of the gas itself dissociation is accomplished more rapidly if either (*a*) the carbon-dioxide gas, as fast as it is formed, is removed from the kiln by a pump, or (*b*) a jet of steam or water is introduced, the effect being to form a mixture of steam and carbon dioxide, which exerts less pressure than would the pure gas alone. In practice the pumping method is rarely used, but the injection of water or steam is quite a common practice.

The burning of a magnesian limestone.—If the limestone, though otherwise pure, contains magnesium carbonate, the effects produced by burning will vary somewhat from those discussed above. Suppose, for example, that a limestone consisting of 60 per cent lime carbonate +40 per cent magnesium carbonate be burned until dissociated. The original limestone consisted of

$$60 \text{ lbs. } CaCO_3(=CaO+CO_2)+40 \text{ lbs. } MgCO_3(MgO+CO_2).$$

While lime carbonate is made up of 56 per cent CaO plus 44 per cent CO_2, magnesium carbonate contains 47.6 per cent MgO plus 52.4 per cent CO_2. The bulk composition of the original limestone may, therefore, be expressed quantitatively as follows:

60 lbs. lime carbonate = { 33.60 lbs. CaO; 26.40 " CO_2 }

40 " magnesium carbonate = { 19.04 " MgO; 20.96 " CO_2 }

The orignal rock, therefore, carries in 100 lbs. 33.60 lbs. of lime (CaO), 19.04 lbs. of magnesia (MgO), and 47.36 lbs. of carbon dioxide (CO_2).

If a rock of this composition be burned, the carbon dioxide will be driven off, as in the case of a pure limestone, but the solid mass remaining will consist partly of lime (CaO) and partly of magnesia (MgO). In addition to this difference, a difference in loss of weight is to be noted. In discussing the burning of a pure non-magnesian limestone it was stated that the driving off of the carbon dioxide meant the loss of 44 per cent in weight. In the case of the particular magnesian limestone here discussed it can be seen that the expulsion of the carbon dioxide is equivalent to a loss of 47.36 per cent in weight.

Dissociation, in the case of a magnesian limestone, appears to be effected at a somewhat lower temperature * than when a non-magnesian limestone is burned, but no accurate data on this point are available.

Classification of limes.—For commercial purposes limes carrying less than 5 per cent of magnesia can be marketed as pure or high-calcium limes; but those containing over 5 per cent differ so markedly in their properties that it is necessary to class them separately. The groups are, therefore, as follows:

GROUP A. High calcium limes: Limes containing less than 5 per cent of magnesia. The limes of this group differ among themselves according to the amount of silica, alumina, iron, etc., contained. A lime carrying

* Probably about 600°–700° C.

less than 5 per cent of such impurities is a "fat" or "rich" lime, as distinguished from the more impure "lean" or "poor" limes.

GROUP B. Magnesian limes: Limes containing over 5 per cent (*usually* 30 per cent or over) of magnesia. These limes are all slower slaking and cooler than the high-calcium limes of the preceding group, and they appear to make a stronger mortar. They are, however, less plastic or "smooth," and in consequence are disliked by workmen. As commercially produced, they usually carry over 30 per cent of magnesia.

Methods and Costs of Lime-burning.

Compared with the complicated processes employed in the manufacture of Portland cement, lime-making is a very simple industry, the only distinctive operation requiring attention being the burning of the limestone. In the present section the types of lime-kilns employed at various localities will be considered, detailed descriptions of several of the more important styles being given. A few brief notes on the utilization of a hitherto practically unused by-product (carbon dioxide) will then be given, after which the costs of lime-manufacture will be considered.

Heat requirements in lime-burning.—In burning limestone to lime heat is required for three purposes:

(*a*) Evaporating any water contained in the limestone.
(*b*) Heating the limestone to its dissociation temperature.
(*c*) Driving off carbon dioxide from the lime (and magnesium) carbonate.

The water in the limestone, however, aids in the dissociation, so that the first heat requirement may be neglected here. Heating the limestone from the air temperature (say 60° F.) to its point of dissociation (about 1700° F. for non-magnesian limestones), assuming that within this range the specific heat of limestone is 0.22, would require, for one ton of limestone $(2000\times22\times1700-60)=721{,}600$ B.T.U. For a magnesian limestone, which loses its carbon dioxide at a lower temperature, this amount would be considerably reduced.

The heat used in the actual dissociation is known quite accurately. One pound of lime carbonate ($CaCO_3$) will require 772 B.T.U. for its dissociation, while one pound of magnesium carbonate would require only 465 B.T.U.* It is of course true that the magnesia is not present in the form of magnesite, but until furnished with some exact determination concerning the dissociation of dolomite we will have to act

* The dissociation heats here quoted are those accepted, from the results of Thomsen and of Johnston, in Technologic Paper, No. 16, U. S. Bureau of Standards.

on the assumption that its heat-requirements are proportional to the lime and magnesia contained.

TABLE 33.

HEAT AND FUEL THEORETICALLY REQUIRED IN BURNING ONE TON OF LIMESTONE.

	Composition of Limestone.	
	100% $CaCO_3$.	50% $CaCO_3$, 50% $MgCO_3$.
Heat required for heating to dissociation-point	721,600 B.T.U.	369,600 B.T.U.
Heat required for actual dissociation	1,544,000 "	1,238,000 "
Total heat requirements	2,265,600 B.T.U.	1,607,600 B.T.U.
Coal theoretically required (14,000 B.T.U. per lb.):		
Intermittent kilns	162 lbs.	115 lbs.
Continuous kilns	110 lbs.	88 lbs.

The above results are to be regarded only as approximations to the truth, because the chemical data on which the calculations are based are not accurately determined, but the figures suffice to show the great economy in fuel consumption which comes from the use of very highly magnesian limestone. With intermediate limestones, however, carrying from 10 to 30 per cent of magnesium carbonate, this apparent economy would not prove real, since the calcite and the dolomite present would not be calcined at the same temperature; but fortunately such intermediate limestones are of comparatively rare occurrence in nature.

Types of lime-kilns.—The types of kilns employed in lime-burning may be grouped as follows:

Intermittent kilns.....(1)
Continuous kilns.
Vertical kiln, mixed feed..... { limestone and fuel fed in alternate layers } .. (2)
Vertical kiln, separate feed...limestone and fuel not in contact (3)
Ring or chamber kiln.....(4)
Rotary kilns.....(5)

(1) *Intermittent kilns* are those in which each burning of a charge constitutes a separate operation. The kiln is charged, burned, cooled,

and the charge is drawn; then the kiln is again charged, and so on. The disadvantages of this intermittent mode of operation are obvious; and kilns of this type are consequently employed only where there is a slight or very irregular demand for the product. Old kilns of this kind can still be seen in farming regions, where charges of lime are burned as the neighborhood demand requires.

These primitive kilns were * "rudely constructed of stone, and were located on the side of a hill, so that the top was easily accessible for charging the kiln with stone and the bottom for supplying fuel and drawing out the lime. In charging, the largest pieces of limestone were first selected and formed into a rough dome-like arch with large open joints springing from the bottom of the kiln to a height of five or six feet. Above this arch the kiln was filled from the top with fragments of limestone, the larger pieces being used in the lower layers, these being topped off with fragments of smaller size. A wood fire was then started under the dome, the heat being raised gradually to the required degree in order to prevent the sudden expansion and consequent rupture of the stones forming the dome. Should this happen, a downfall of the entire overlying mass would take place, putting out the fire and causing the total loss of the contents of the kiln. After a bright heat was once reached throughout the mass of stone, it was maintained for three or four days to the end of the burning. This was indicated by a large shrinkage in volume of the contents of the kiln, the choking up of the spaces between the fragments, and the ease with which an iron rod could be forced down from the top. The fire was then allowed to die out and the lime was gradually removed from the bottom. It was in this manner that all the lime used in Indiana for many years was burned, and in some localities these temporary intermittent kilns are still in operation. The process of burning is simple and cheap, the only expense being for blasting the stone and preparing the fuel. Possibly but one or two kilns were necessary to supply a neighborhood for a year. These were operated for a week or two when required and remained idle for the remainder of the year.

"As the population increased, the demand for lime became greater, and in many places permanent kilns lined with fire-brick were erected. These were the old-fashioned stone 'pot-kilns' of a quarter century ago. On the inside they were usually circular in horizontal section, tapering slightly, by a curve both up and down, from the circle of largest diameter, which was from 4 to 6 feet above the bottom. A kiln 10 to 11 feet in greatest diameter was 25 to 28 feet high, 5 to 6 feet in diameter at

* Blatchley, S. W. 29th Ann. Rep. Indiana Dept. Geology, pp. 225–227, 1904.

the top and 7 to 8 feet at the bottom. There was an arched opening on one side at the bottom 5 or 6 feet high, through which the wood was introduced and the burnt lime removed. A horizontal grating on which the fire was built was usually placed 1 or 2 feet above the bottom.

" In all these intermittent kilns there was an enormous loss of heat at each burning, for the quantity of fuel necessary to raise the contents of the kiln and the thick stone and brick walls to the necessary degree of heat had to be repeated each time the kiln was charged. Moreover, the stone nearest the dome arch in the kiln was liable to become injured by overburning before the top portions of the charge were thoroughly calcined."

(2) *Vertical kilns with mixed feed.*—In kilns of this type the limestone and fuel are charged into the kiln in alternate layers. As the burning progresses burned lime is drawn from the bottom of the kiln, while fresh layers of limestone and fuel are added at the top.

The advantages of *mixed-feed* kilns, as compared with the separate feed-kilns described below, are (*a*) that they are cheaper to construct, (*b*) that they are somewhat more economical of fuel, and (*c*) that they give for the same size of kiln a larger output in the same time. These advantages are partly counterbalanced by the disadvantages to which they are subject, these being (*a*) that the burned lime is discolored to some extent by its contact with the fuel, (*b*) that the ashes of the fuel cannot readily be separated from the burned lime, thereby lowering the quality of the product, and (*c*) that a part of the fuel ashes may clinker on the outside of the lumps of lime, preventing even and satisfactory burning.

To sum up the advantages and disadvantages: the " mixed-feed " kiln is cheaper both in first cost and in operating expenses; its product is good enough for most ordinary purposes, but is not as evenly burned or as white as is the product of a " separate-feed " kiln.

At a small Pennsylvania lime-plant three vertical mixed-feed kilns are in use. Each of these kilns takes about 24 tons of stone per day, requiring the services of six quarrymen to keep the three kilns supplied. Bituminous slack is used for fuel, the consumption being 26 lbs. slack per bushel (75 lbs.) of lime, equivalent to a fuel consumption of 34.7 per cent on the weight of lime produced. This ratio if correct is enormous compared to natural- or even Portland-cement plants, and points to unusually inefficient management. As a general rule, a vertical mixed-feed kiln may be expected to produce lime with a fuel consumption of from 15 to 25 per cent of the weight of clean product. The cause of

this apparently high consumption is that so much of the product is usually unfit for use.

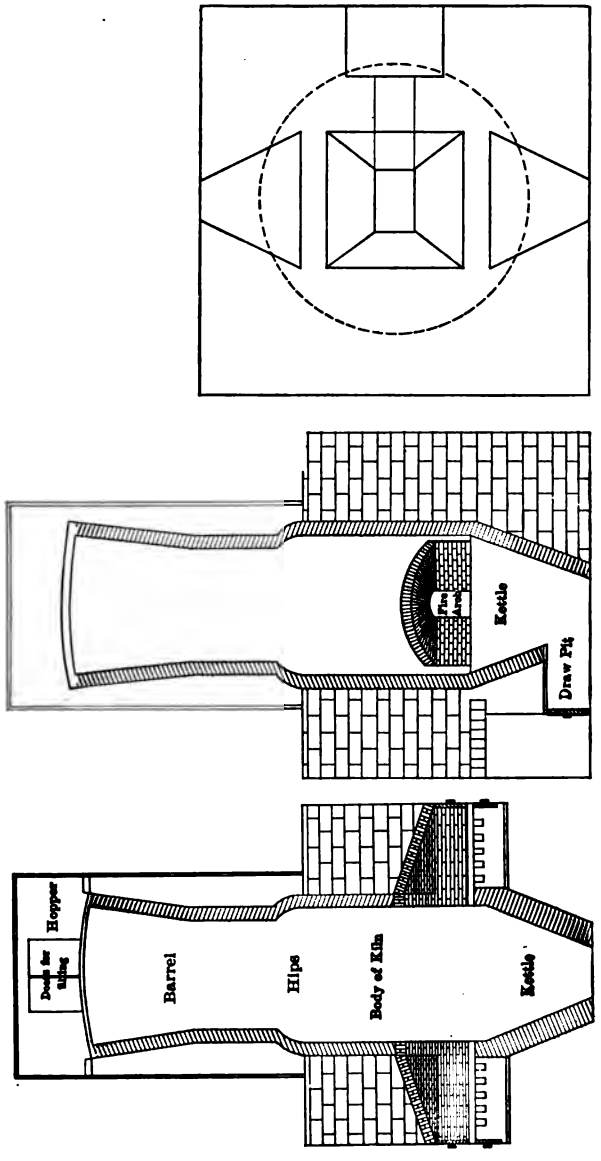

FIG. 23.—Plan and sections of lime-kiln.

The Aalborg or Schöfer kiln, one of the best types of stationary kilns for cement practice, has been employed in a somewhat modified

form for burning lime and hydraulic lime. The lime-kiln of this type is shown in Fig. 24. The limestone is fed in at the charging door, *B*, while the fuel is charged through the chutes *f*, *f*. The mass of limestone in the preheating chamber *D* is dried, heated, and partly decarbonated before it enters the burning-zone, when the decarbonation is complete. The cooling-chamber *C* reduces the temperature of the burned lime

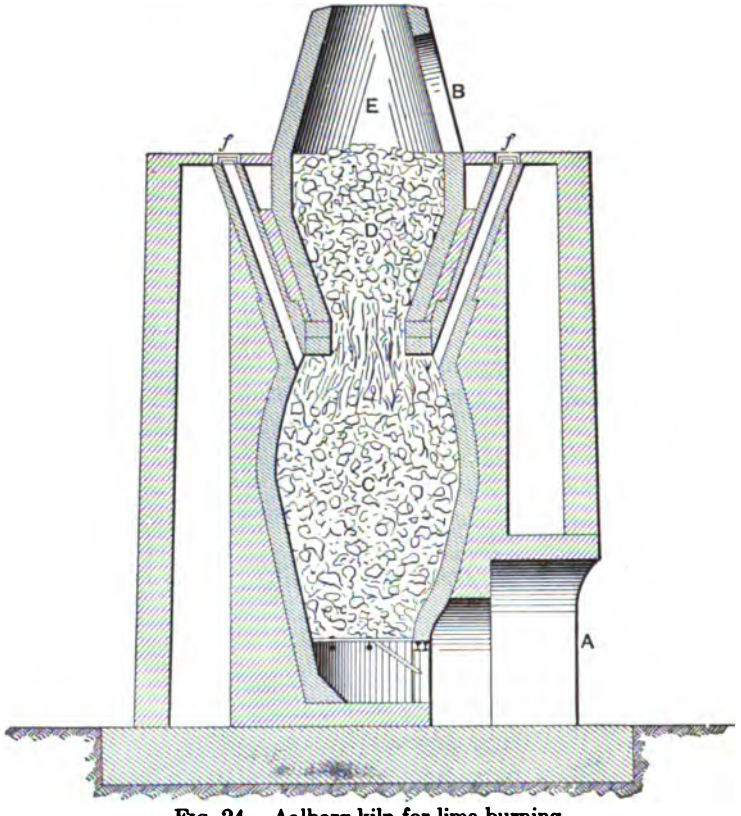

FIG. 24.—Aalborg kiln for lime-burning.

and incidentally heats the air which passes through it to supply combustion. These features make the Aalborg kiln very economical in fuel consumption. Each kiln will turn out 15 to 20 tons per day, and will use 220 to 260 pounds of coal per ton of quicklime burned, equivalent to a fuel consumption of 10 to 12 per cent on the weight of the product, which is very close to the theoretical minimum.

(3) *Vertical kilns with separate feed.*—Kilns of this type, which are now used at most of the larger lime-burning plants, are equipped with

separate fireplaces to carry the fuel, distinct from the body of the kiln. These fireplaces may be set either in the wall of the kiln, the usual position when a stone-walled kiln is used, or outside of the kiln-shell. The kiln body proper contains the charge of limestone, while the fuel is fed and burned in these fireplaces or furnaces. The limestone, therefore, does not come into direct contact with the fuel, but only with the hot fuel gases. Other things being equal, kilns of this type could not show quite as high a fuel efficiency as kilns in which the limestone and fuel are charged together in alternate layers. The product, however, is of a much higher grade, for it is not discolored by contact with the fuel, and it contains no fragments of unburned fuel or fuel ashes and clinkers. With average care in feeding and burning, it is probable that at least 90 per cent of the product from a kiln of this type will be a well-burned clean white lime, as compared with the 75 or 80 per cent obtainable from mixed-feed kilns. As the fuel-burning apparatus is entirely distinct from the body of the kiln, the firing can be kept under better control, so that the percentage of underburned and overburned material in the product should be materially decreased.

Kilns of this type are commonly 35 to 50 feet in height and 5 to 8 feet in inside diameter, with either two or four fireplaces or " furnaces."

The Keystone kiln, described in detail below, may be taken as fairly representative of this type of lime-kiln. Its construction can be clearly seen from Fig. 25, which shows the kiln with a portion of the shell cut away to exhibit the interior, and with the side wall of the furnace removed to show its construction. The kiln from top to floor is a heavy steel shell lined with fire-brick. The base of the kiln below the firing platform is made from very heavy steel plates, reinforced on the inside by numerous stiffening-ribs. The furnaces are carried on steel platforms which extend a sufficient distance in front of the firing-doors to give a convenient working space. In addition to being supported at the inner ends by attachment to the shell of the kiln the steel beams which floor the platforms rest at their outer ends on steel columns.

In operating this kiln the flame from the coal (or wood) burned in each furnace is directed through two large openings in the kiln shell and lining directly against the limestone which fills the kiln. These openings, as well as the kiln shell and the furnaces, are lined with fire-brick.

As the lime passes the burning-zone it falls into a " cooling-cone " made of steel plates. This is an inverted hollow frustum of a cone suspended from a heavy cast-iron plate, which in turn is supported

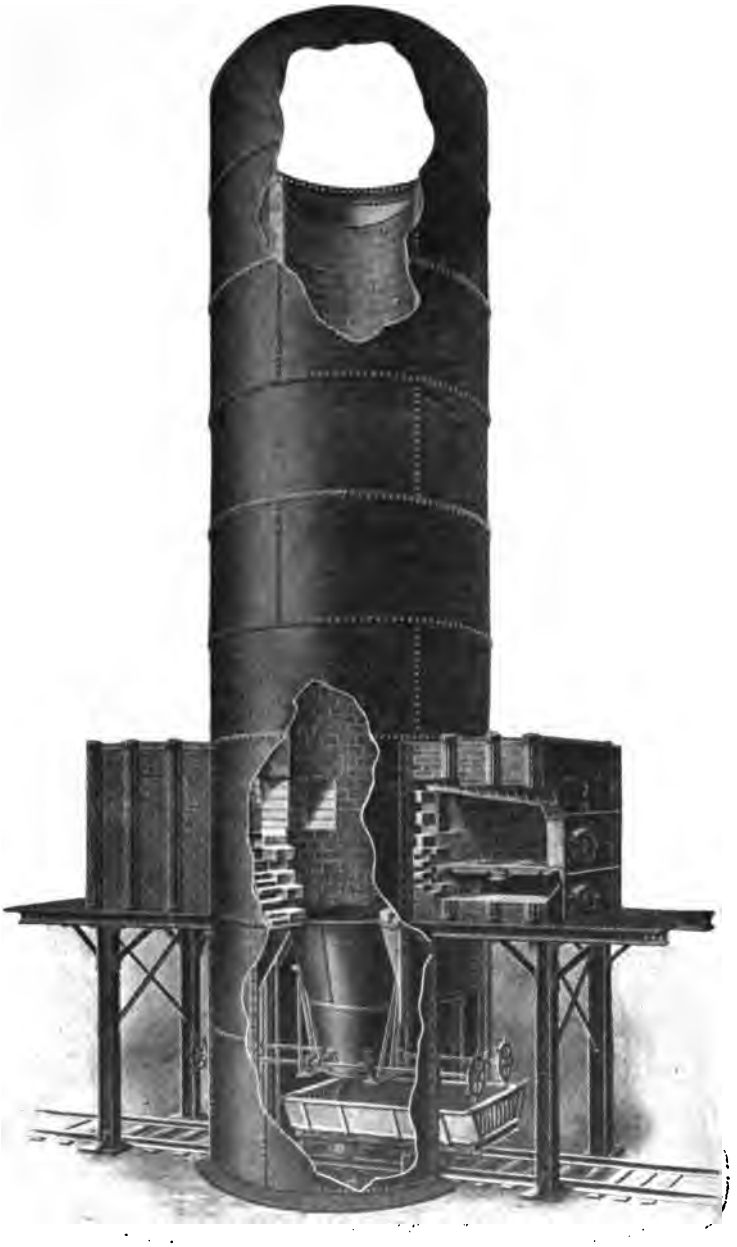

FIG. 25.—Keystone lime-kiln.

by gusset plates riveted to the base of the kiln. The cooling-cone varies from 6 to 6½ feet in diameter at top, according to the size of the kiln, and is 7 feet high. The burned and partly cooled lime is drawn from the cone by means of shears or draw-gates at its bottom. These gates are operated by hand-wheels which project outside of the kiln base, thus removing the operator from the dust and heat of the lime. The lime can be discharged into a car run in under the cooling-cone or on the floor. The heated air which ordinarily would accumulate around the cooling-cone is discharged into the ash-pit under the grates, which adds considerably to the efficiency of the furnace. Arrangement can also be made for placing a steam-jet in the hot-air passage so as to provide forced draft if desired.

TABLE 34.

DIMENSIONS OF KEYSTONE LIME-KILNS.

	No. 1	No. 2.	No. 3.
Outside diameter of shell	10 ft.	11½ ft.	12 ft.
Inside diameter of lining	5 "	6 "	6½ "
Total height	38 "	43 "	48 "
Output per day, in bushels of 70 lbs	200–250	250–300	300–350

Many patents have been taken out to cover improvements in various details of the ordinary lime-kiln. One of these patented devices is shown in Fig. 26, where boilers are inserted in the kiln arches so as to utilize the waste heat of the kiln. The boilers, in turn, are used to develop the power needed for running drills, hoists, and other machinery in the quarry and mill.

(4) *Ring or chamber kilns.*—Chamber kilns of the Hoffman type, though never used in America, are in somewhat extensive use in Europe for both lime and Portland-cement burning. They are described on later pages in connection with the burning of Portland cement. When used for burning lime in Europe, a fuel consumption of 400 to 450 lbs. coal per ton (2000 lbs.) of burned lime is attained in common practice, while lower consumption can be expected under favorable conditions. The Hoffman kiln is, of course, a great improvement in both economy and quality of product on the old style of vertical kiln, but it is doubtful if it gives better results than the modern kilns now in use in the more important American lime-plants.

Gen. Q. A. Gilmore stated * in 1871 that a Hoffman kiln used for lime-burning at Llandulas, Wales, produced about 80 tons of lime per day at the following detailed cost:

* Gillmore, Q. A. A practical treatise on Coignet-Béton and other artificial stone, pp. 71–72, 1871.

Cost of quarrying stone, including tools	$0.31½
Charging kiln	0.10½
Drawing kiln	0.07½
Wages of burners	0.07½
Fuel at $1.75 per ton	0.37½
Managing expenses, etc	0.31½
Cost of lime per ton	$1.25

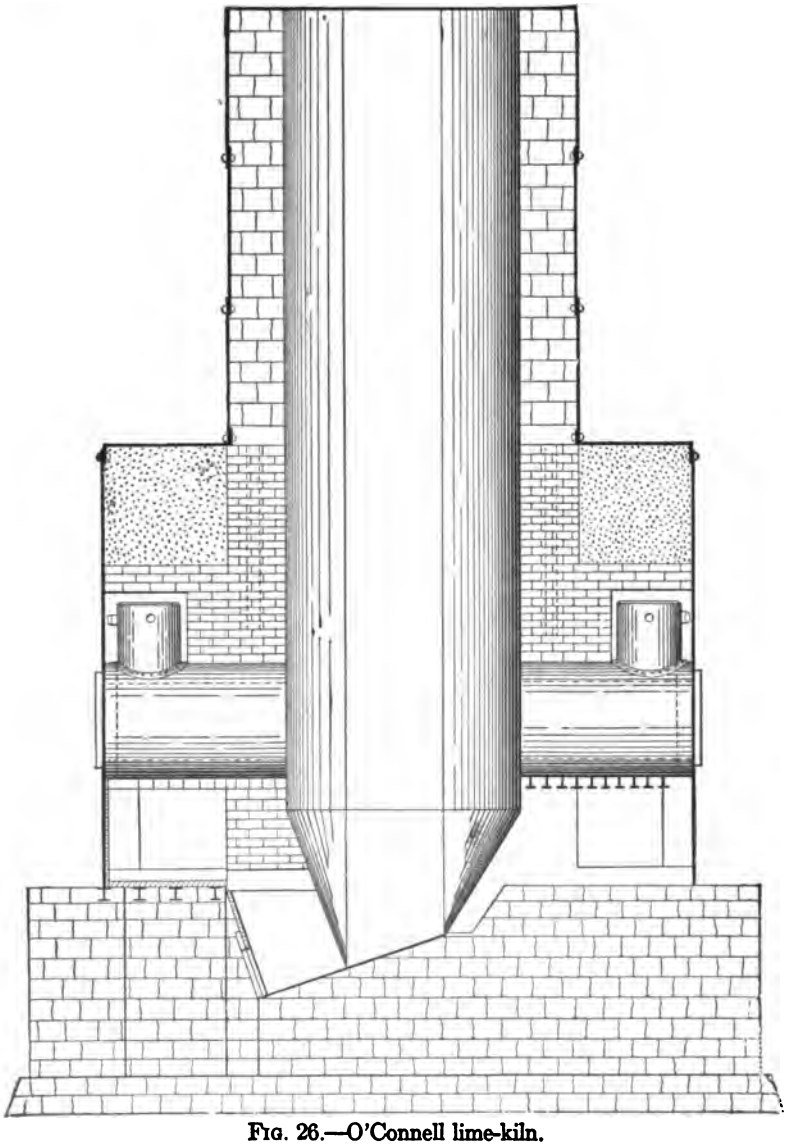

FIG. 26.—O'Connell lime-kiln.

(5) *Rotary kilns.*—The successful use of the rotary kiln in the Portland cement industry led, of course, to experiments with its use in the burning of lime; but so far very few plants have adopted the rotary kiln for this purpose. Its essential disadvantage—high fuel consumption—appears just as strikingly in the lime industry as in cement manufacture, while there are several additional troubles, due to conditions in the lime industry.

For successful operation, the material fed to a rotary kiln should be of fairly even size, and preferably finely ground; these conditions ensure steady operation, even burning and large output. But in the lime trade there is still objection to anything except lump lime, so that unless all of the product from a rotary goes to a hydrating plant there are trade objections to the use of the kiln. Further than that, it is difficult to keep the rotary temperature down to an economical lime-burning heat, so that an impure stone is apt to give a large amount of clinkers.

Under these circumstances, the use of the rotary kiln for making lime that goes to the general trade is as yet limited. It is least disadvantageous when either the limestone is very pure, or when it is naturally very fragile. The use of the rotary has grown slowly until now there are some thirty kilns of that type used in the United States for lime burning. Its use may be expected to increase as the demand for hydrated lime and for chemical lime grows larger.

The overburning of lime.—There are many references in the literature of lime manufacture, to " overburned " lime, a term which hardly fits in with the known facts of the case. A pure limestone, i.e., one that is free from silica, alumina and iron oxide—will not " overburn " at any temperature that will be reached in a lime kiln.

What we call " overburning " is in reality the clinkering of a portion of the burned product, due to combination (during the burning) of part of the lime with silica, alumina or iron. The phenomenon has two distinct though similar causes.

(1) *Clinkering of an impure limestone.*—If the limestone which is being burned carries much in the way of clayey impurities—silica, alumina, iron oxide—there is danger that the temperature reached in the lime kiln will be high enough to cause combination of the lime with these constituents. The result will be the sintering of clinkering of a portion of the product. It is in reality the formation of a certain amount of grappiers or natural cement. In American practice these " overburned " portions are thrown away; in Europe they are carefully saved and ground to make the well-known and valuable " grappier cements " described in Chapter XIV. Clinkering or " overburning " of

TABLE 35.

TESTS OF LIME-KILN EFFICIENCY (EMLEY).

Number	1 (Using Dolomite).		1 (Using Calcite).		2.		3.		4.		5.		6.	
Process Used	Rotary Kiln.		Rotary Kiln.		Eldred Process.		Schmatolla Process.		Forced and Induced Draft		Natural Draft.		Producer Gas.	
	Millions of B.T.U.	Per Cent.	Millions of B.T.U.	Per Cent.	Millions of B.T.U.	Per Cent.	Millions of B.T.U.	Per Cent.	Millions of B.T.U.	Per Cent.	Millions of B.T.U.	Per Cent.	Millions of B.T.U.	Per Cent.
Heat put in:														
1. From coal fired....	*209.0 † 61.9	100.0	*139.0 † 28.6	100.0	146.0	99.0	531.0	99.6	148.0	95.5	208.0	100.0	157.0	99.3
2. From power for fans..	0	0	0	0	0.17	0.1	1.9	0.4	0.1	0.1	0	0	0.3	0.0
3. From steam blown in.	0	0	0	0	0	0	0	0	6.7	4.4	0	0	*1.0	0.7
Heat used:														
4. To burn the lime.....	101.0	37.2	64.1	38.2	56.0	38.3	288.0	54.0	68.4	44.1	64.3	30.9	55.7	35.3
5. To create the draft...	20.6	7.6	14.4	8.6	0.17	0.1	1.9	0.4	6.8	4.4	31.7	15.2	1.1	0.7
6. For power.....	35.5	12.4	19.8	11.7	0	0	0	0	0	0	0	0	0	0
Heat lost:														
7. By combustible in ash.	1.7	0.6	0.8	0.5	11.7	8.0	3.3	0.6	6.4	4.1	10.9	5.2	21.8	13.8
8. By hot lime.....	0	0	0	0	0.68	0.5	5.4	1.0	12.40	8.0	1.8	0.9	1.55	1.0
9. By stack gases.....	49.6	18.3	22.0	13.1	35.8	24.5	122.0	22.9	37.3	24.1	3.7	1.8	20.9	13.2
10. By radiation and conduction (by difference).....	64.6	23.9	46.9	27.9	41.8	28.6	112.0	21.1	23.7	15.3	95.5	46.0	57.0	36.0
Heat efficiency.....	.....	37.2	.....	38.2	.....	38.3	.....	54.0	.....	44.1	.....	30.9	.....	35.3
Fuel ratio:														
Theoretical.....	11.4		10.7		9.85		10.45		9.74		9.45		9.25	
Actual.....	4.27		4.10		3.78		5.65		4.29		2.92		3.27	
Capacity (tons per kiln per day).....	31.5		31.5		10.6		53.8		12.6		11.7		10.4	

* In producer. † Under boiler.

this type may begin at quite low temperatures in a lime carrying 10 per cent or more of clayey impurities; and it may occur locally with stone carrying only 5 per cent.

(2) *Clinkering due to ash or linings.*—Clinkering or "overburning" of a portion of the kiln product may also occur in another way, the clayey matter being derived, not from natural impurities in the limestone, but from outside sources. In mixed-feed kilns the ash of the coal is likely to contribute such constituents, and to cause clinkering of some of the lime. In other types of kiln, there will be at high temperatures attack by the lime on the kiln-linings; and the same result will be brought about.

Actual fuel requirements.—In a preceding section (page 100) it was seen that to burn a limestone to lime required on the average, in theory, not much over 100 lbs. of coal per ton of limestone used, or say 200 lbs. of coal per ton of lime produced. In actual practice these theoretical amounts are of course heavily exceeded; the usual fuel consumption will range around three to five times the amount theoretically required.

A series of actual tests covering the utilization and waste of the heat employed was carried * on by W. E. Emley, of the U. S. Bureau of Standards some years ago. The results are summarized in Table 35 following.

Type of fuel actually used.—The following data on types of fuel actually used at American lime plants during recent years, are summarized from publications of the United States Geological Survey:

TABLE 36.

TYPE OF FUEL USED AT AMERICAN PLANTS.

Kilns Using	1913.	1917.	1918.
Coal	1334	1138	885
Coke	123	189	151
Coal and coke	22	51	37
Oil	54	27	24
Natural gas	30	25	21
Producer gas	76	86	76
Wood	479	268	194
Coal and wood	220	182	182
Mixed or unspecified	....	....	....
Total kilns reported	2338	1966	1570

Utilization of carbonic-acid gas from lime-kilns.—During the burning of limestone to lime an enormous amount of carbonic-acid gas

* Reported in Technologic Paper, No. 16, U. S. Bureau of Standards, 1913.

(carbon dioxide, CO_2) is driven off and usually wasted. The extent of this waste may be appreciated when it is recalled that 100 lbs. of pure limestone would give on calcination 56 lbs. of quicklime and 44 lbs. of carbon dioxide. To put the matter in another way, for every ton (2000 lbs.) of lime made 1571 lbs. of carbon dioxide are thrown into the atmosphere. During recent years, therefore, over one and a half million tons of carbon dioxide were produced—and wasted—from the lime-works of the United States. Few attempts have been made by lime-manufacturers to utilize this valuable by-product, though the manufacture of carbonic acid, as an independent industry, has become of great importance.

Cost of lime-manufacture.—With the exception of a comparatively few large and well-managed lime-plants, lime-manufacture in the United States is not so steadily and economically handled as to give much basis for generalizations concerning costs. The result is that the data obtainable are rarely definite enough to be of much service. The following is probably as fair a statement of the case as can be made. The data given refer to unit costs of labor and materials as of the 1903–1913 price level, and should be changed as earlier noted (pp. 7–9) for use in any other period.

The principal items to be considered in estimating the cost of lime-manufacture are:

(1) Interest on cost of plant and quarry.
(2) Cost of quarrying limestone.
(3) Cost of fuel for burning.
(4) Labor costs, exclusive of quarry.

The interest on cost of plant and quarry will vary greatly according to the steadiness with which the plant is operated. This is, of course, true with regard to the same item in the cement industry, but lime-plants are in general subject to greater fluctuations in output. The estimates given below of interest charges per ton of lime are therefore given a very wide limit, but it is believed to be impracticable to place them more definitely.

The cost of quarrying is also variable, but within narrower limits. In large, carefully managed quarries located near the kilns, and with stone and stripping so arranged as to admit of cheap extraction, the cost of quarrying the limestone and transporting it to the kiln may fall as low as 25 cents per ton. This cost is attained in Portland-cement quarries in the Lehigh district of Pennsylvania, and in a number of natural-cement and lime quarries elsewhere. On pages 352, 355 will

be found further details as to cost of quarrying, one of the examples being of the costs at a quarry worked both for Portland cement and for lime. With average skill in locating and managing the quarry, it is probable that the cost of quarrying need never rise above 40 or 45 cents per ton of rock. Allowing for waste and loss by under or over-burning, 2 tons of limestone will be required to make 1 ton of lime. This would give as the probable limits of cost of quarrying 50 to 90 cents per ton of burned lime.

Wood is still used for fuel at many lime-kilns, in which case the cost of fuel may be merely nominal or may be very high. When coal is used for fuel in a modern kiln, the coal consumption per ton of burned lime may vary from 300 to 500 lbs. These limits have been assumed in the estimate below, while the cost of coal has been taken as varying from $2 to $3 per ton. These prices are fairly representative for most of the lime-plants of the country.

Labor costs are estimated with a rather liberal maximum limit.

The final results of these calculations are shown below.

TOTAL COST OF LIME-MANUFACTURE PER TON.

Interest on cost of plant and quarry	$0.05 to $0.20
Taxes, minor supplies, etc	0.10 " 0.25
Cost of quarrying two tons of limestone	0.50 " 0.90
Cost of fuel for burning	0.30 " 0.75
Cost of labor, exclusive of quarrymen	0.25 " 0.80
Total cost per ton of burned lime, in bulk (2000 lbs.)	$1.20 to $2.90

This corresponds to costs of 4.2 to 10.15 cents per bushel of 70 lbs. The minimum estimate represents what might be attained by a good modern plant, run steadily and under exceptionally favorable conditions as regards quarrying, fuel, and labor. The maximum estimate could easily be exceeded by the small or unsteadily operated plants. The average cost throughout the entire country is probably in the neighborhood of 6 to 8 cents per bushel.

Actual costs of lime-manufacture in 1900.—In connection with the above estimates of cost it is of interest to compare certain statistics collected by the Census Bureau in 1900 and published in vol. 7, Reports Twelfth Census, pages 274–277. The tables on the pages cited give total costs of various elements in lime- and cement-manufacture in all the states during 1900. As the figures for lime, natural cement, and Portland cement are tabulated together, most of the tables are of little value for our present purpose. In the ten states considered below, however, no natural- or Portland-cement plants were in operation during

1900, so that the statistics for these states must necessarily apply only to the lime industry. The data relating to these ten states have accordingly been slightly rearranged and are shown in the following table.

TABLE 37.

COST OF LIME-MANUFACTURE DURING 1900 IN TEN STATES.

State	Arkansas.	Connecticut.	Iowa.	Maine.	Massachusetts.
Number of plants	5	11	28	20	11
Total capital	$53,894	$250,392	$663,830	$1,942,007	$115,639
In land	11,598	71,720	89,100	485,338	20,100
In buildings	10,865	65,550	159,325	681,515	28,700
In machinery	9,396	26,915	261,785	143,225	16,800
In cash, etc	22,125	86,207	153,620	631,929	50,039
Salaried officials	6	12	38	34	3
Total salaries	$3,075	$9,640	$26,588	$26,296	$2,640
Laborers	78	171	302	582	130
Total wages	$15,600	$71,938	$145,382	$248,371	$69,823
Rent, taxes, etc	$6,409	$21,932	$68,488	$97,878	$7,630
Limestone, cost of	$21,097	$86,759	$134,300	$347,344	$67,826
Fuel, cost of	8,150	59,005	41,564	196,991	54,257
Mill supplies, etc	.....	963	4,345	33,101	40
Freight	250	2,025	1,305	68,803	310
Value of product	$70,900	$286,640	$543,267	$1,226,972	$261,477

State	Missouri.	Rhode Island.	Tennessee.	Vermont.	West Virginia.
Number of plants	31	3	12	13	7
Total capital	$797,926	$26,150	$158,886	$176,825	$256,860
In land	201,852	8,000	39,300	51,900	142,500
In buildings	232,119	4,000	27,680	31,450	28,500
In machinery	107,675	2,500	20,751	19,925	9,160
In cash, etc	256,280	11,650	71,155	73,550	76,700
Salaried officials	48	1	4	2	15
Total salaries	$46,350	$360	$2,350	$1,400	$9,260
Laborers	583	40	167	182	128
Total wages	$206,837	$16,230	$50,665	$57,257	$47,200
Rent, taxes, etc	$40,045	$9,752	$2,492	$9,367	$1,400
Limestone, cost of	$100,174	$8,314	$16,614	$36,804	$6,175
Fuel, cost of	109,974	8,700	20,305	45,112	24,840
Mill supplies, etc	2,960	125	1,110	7,636	30
Freight	20,802	.....	1,857	6,000	3,800
Value of product	$600,432	$48,089	$166,423	$207,524	$109,393

As the total quantities of lime produced are not stated, it is impossible to reduce the total costs given in the table to costs per ton or bushel of product. A simple calculation, however, enables us to reduce them to percentages of the total cost, so that the relative importance of the various elements making up this total can be readily noted. In Table 38, below, this has accordingly been done. The interest charges have been taken at 6 per cent of the total capital, and no specific allowance has been made for depreciation or repairs, as these items for the year in question must appear under one of the other headings. The value of the product has also been calculated, in percentages of the total cost.

TABLE 38.

ELEMENTS OF COST OF LIME-MANUFACTURE, EXPRESSED IN PERCENTAGES OF TOTAL COST.

	Ark.	Conn.	Iowa.	Maine.	Mass.	Mo.	R. I.	Tenn.	Vt.	W. Va.	Average.
Interest.....	5.6	5.6	8.6	10.3	3.3	8.5	3.4	9.1	6.1	14.2	7.47
Salaries.....	5.3	3.6	5.9	2.3	1.3	8.1	0.8	2.3	0.8	8.6	3.90
Wages.....	26.9	26.8	31.4	21.9	33.3	35.9	36.1	48.3	32.9	43.7	33.72
Taxes, etc...	11.1	8.2	14.8	8.6	3.7	6.9	21.7	2.4	5.3	1.3	8.40
Limestone...	36.5	32.5	29.1	30.6	32.4	17.4	18.4	15.8	21.1	5.7	23.95
Fuel.....	14.1	22.1	9.0	17.3	25.9	19.1	19.3	19.3	25.9	23.0	19.50
Supplies.....	0.0	0.4	0.9	2.9	0.0	0.5	0.3	1.1	4.4	0.0	1.05
Freight.....	0.5	0.8	0.3	6.1	0.1	3.6	.....	1.7	3.5	3.5	2.01
Total cost.	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.00
Value of product...	122.7	107.2	117.6	108.1	124.8	104.0	106.7	158.6	1.191	1.012	117.00

TABLE 39.

LIME BURNED AND SOLD IN THE UNITED STATES IN 1909–1920.

	Quantity (Short Tons).	Value.	Average Price per Ton.	Number of Plants in Operation.
1909	3,484,974	$13,846,072	$3.98	1232
1910	3,505,954	14,088,039	4.02	1125
1911	3,392,915	13,689,054	4.03	1139
1912	3,529,462	13,970,114	3.96	1017
1913	3,595,390	14,648,362	4.07	1023
1914	3,380,928	13,268,938	3.92	954
1915	3,622,810	14,424,036	3.98	906
1916	4,073,433	18,509,305	4.54	778
1917	3,786,364	23,807,877	6.29	595
1918	3,206,016	26,808,909	8.36	496
1919	3,330,347	29,448,553	8.84	539
1920	3,570,141	37,543,840	10.52	515

Statistics of the lime industry.—The lime industry, in the United States as elsewhere, has grown during recent decades at rather a slow rate, compared with other great industries. This has been accompanied by a change in the character of its output, more and more lime each year going to the various chemical uses, while the building lime proper shows a tendency to decrease.

CHAPTER VIII.

COMPOSITION AND PROPERTIES OF LIME.

THE lime (or "quicklime") resulting from the burning of a pure limestone is a white solid, with a specific gravity of 3.09 to 3.15. As packed, it will weigh about 60 lbs. per cu. ft., or 70–75 lbs. per bushel. When made from a limestone rock, the lime should be in lumps, the occurrence of powder or dust proving that the lime has been exposed to the air so much since burning that air-slaking has begun. When the lime has been made from shells, marl, highly crystalline marbles, soft chalk, or shelly limestones, however, it will often come from the kilns in small fragments, which in this case is no sign of deterioration.

If the raw material is impure, containing much clayey matter or iron oxide, the resulting lime will not be white, but will vary from yellowish to gray or brown in color, according to the amount and kind of impurities present. It will also, in general, slake much slower than would a purer product.

High-calcium vs. magnesian limes.—The relative merits of these two classes have been frequently discussed in text-books and technical journals, and are still subjects of controversy. The facts of the case, however, seem to be simple enough and may be summarized as follows:

High-calcium limes slake rapidly on the addition of water, and evolve much heat during slaking. They also expand greatly, giving a large bulk of slaked lime. Magnesian limes slake very slowly, and evolve very little heat during the process. Their expansion is also less; so that, taking equal weights, they give less bulk of slaked lime.

Owing to the slowness and coolness with which the magnesian limes slake, there is some danger that the average mortar-mixer * will not give them sufficient time to slake thoroughly. Owing to the fact that they make less bulk of slaked product than do the high-calcium limes, the average contractor or builder thinks that they are too expensive. But, on the other hand, they are very much stronger in long-time tests than the high-calcium limes, and will therefore carry much more sand.

* A human, not mechanical, mortar-mixer is here spoken of.

This fact is brought out, for one instance, by the tests given on page 125.

Composition of commercial high-calcium limes.—The non-magnesian or high-calcium limes as marketed will rarely carry less than 90 per cent of lime oxide (CaO), while they commonly carry over 95 per cent. The remaining 5 or 10 per cent is made up of magnesia (MgO), silica (SiO_2), alumina (Al_2O_3), iron oxide (Fe_2O_3), and a little carbon dioxide and water. In the following table a number of analyses of representative high-calcium limes are given.

TABLE 40.

ANALYSES OF HIGH-CALCIUM LIMES (U. S.).

No.	Silica (SiO_2).	Alumina (Al_2O_3) and Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Carbon Dioxide (CO_2) and Water.
1*	0.18	0.26	98.44	0.98	0.32
2	0.37	0.21	97.11	0.56	n. d.
3	1.69	n. d.	96.11	0.11	n. d.
4	1.01	1.30	97.72	n. d.	n. d.
5	0.81	0.75	98.30	n. d.	n. d.
6	1.14	0.17	95.66	0.76	3.00
7	0.36	0.15	98.13	0.42	0.80
8	0.81	0.47	96.63	0.88	0.12
9	1.96	0.94	95.60	0.14	1.36
10	3.42	1.21	94.26	0.32	0.79
11	0.79	0.26	97.48	1.40	n. d.
12	3.2	1.4	94.0	1.40	n. d.
13	1.88	2.03	91.93	3.06	n. d.
14	1.70		96.46	0.64	1.20
15	0.80		97.60	0.36	1.24
16	0.23	1.29	97.64	0.80	n. d.
17	1.06	0.58	95.50	tr.	2.08
18	1.93	0.27	94.07	0.79	3.04
19	3.20	0.80	94.80	1.21	n. d.
20	0.43	0.36	97.82	0.12	n. d.
21	0.56	0.22	97.89	1.05	n. d.
22	0.25	0.15	97.46	0.73	1.41
23	0.15	0.16	97.82	0.85	1.02
24	tr.	tr.	98.47	1.12	0.45
25	0.10	0.12	99.29	0.46	n. d.
26	0.02	tr.	98.84	0.12	1.02
27	0.38	0.65	98.26	0.30	n. d.
28	0.14	tr.	99.23	0.60	n. d.
29	0.27	0.19	98.14	1.40	n. d.
30	0.18	0.26	98.44	0.98	0.32
31	0.30	0.42	98.24	0.56	0.54
32	2.22	n. d.	96.93	0.85	n. d.
33	0.42	0.33	97.71	1.15	0.32
34	0.78	0.52	98.40	0.10	n. d.
35	1.38	0.62	97.80	0.18	n. d.

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Limes of this type slake rapidly when water is added and develop much heat during slaking. They also expand notably, so that the resulting paste (slaked lime) will be much more bulky than the original lime.

Lean or poor limes.—A lime containing over 5 per cent of such impurities as silica, alumina, and iron oxide will usually be dark in color, comparatively slow slaking, and difficult to trowel in working. Such limes are known as " lean " or " poor " limes. In a few cases the impurities are so evenly and finely distributed throughout the original limestone that on burning the limestone a certain amount of combination takes place between the lime (CaO) and the impurities. This gives slighly hydraulic properties to the product. Ordinarily, however, no such chemical combination takes place on burning, and the impurities simply serve to depreciate the quality of the lime produced.

The following analyses (Table 41) are of lean limes produced at various localities in the United States.

TABLE 41.

ANALYSES OF LEAN LIMES.

Silica (SiO_2).....	2.43	3.24	3.50	1.62	10.20	5.50	6.29
Alumina (Al_2O_3)..... Iron oxide (Fe_2O_3)...	6.80	4.26	3.92	2.62	3.60	1.99	0.42 0.33
Lime (CaO).....	81.38	81.92	83.20	82.40	81.33	84.40	85.49
Magnesia (MgO).....	1.34	n. d.	n. d.	n. d.	1.17	1.80	0.31

The last of the above analyses is of a lime made by burning oyster-shells in a mixed-feed kiln. In this case the impurities shown in the lime are largely the result of coal-ash taken up by the lime during manufacture.

Composition of commercial magnesian limes.—In discussing the classification of limes, pages 98, 99, it was stated that limes carrying over 5 per cent of magnesia were to be grouped commercially as magnesian limes. In the present place this statement will bear discussing in somewhat more detail.

In theory a limestone can carry anywhere from 0 to 45.65 per cent of magnesium carbonate ($MgCO_3$). In the first case it would have the composition of the mineral calcite ($=CaCO_3$), in the second that of the mineral dolomite ($CaCO_3+MgCO_3$), while the intermediate stages falling between these two limits (0 and 45.65 per cent $MgCO_3$) would be known simply as magnesian limestones. A further theoretical conclusion is that such intermediate stages would occur approximately as commonly as the extreme stages.

In practice, however, we find that this last theoretical deduction does not hold. If a large series of limestone analyses be compared, it will be found that by far the great majority of them are of the two extremes of the series. That is to say, actual limestones are either *very* low in magnesia or *very* high in it. This condition causes the product made by burning limestone to fall usually in one of the two following classes:

A. High-calcium limes: magnesia less than 5 per cent.
B. High-magnesium limes: magnesia over 30 per cent.

Intermediate limes are of course burned, but they are comparatively rare. Analyses 10, 11, 12, and 13 of Table 42 are of such intermediate types, carrying respectively 7.41, 7.52, 13.42, and 6.08 per cent of magnesia.

The composition of the typical magnesian limes is well shown by analyses 1–9, inclusive, of Table 42.

TABLE 42.

ANALYSES OF MAGNESIAN LIMES (U. S.).

Number.	Silica (SiO_2).	Alumina (Al_2O_3) and Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Carbon Dioxide (CO_2), Water, etc.
1	0.42		56.57	42.56	0.10
2	7.25	1.24	55.74	34.07	1.62
3	0.88		56.81	37.98	2.84
4	0.80		58.00	38.45	2.80
5	1.61	0.17	57.44	40.36	0.41
6	2.95	1.35	58.33	37.37	n. d.
7	0.46	1.10	55.49	42.31	0.64
8	0.07	2.62	63.03	34.15	0.13
9	0.35	0.49	59.20	38.38	1.80
10	1.09	1.74	81.83	13.42	1.92
11	n. d.	0.38	91.72	7.52	n. d.
12	1.78	0.75	90.07	7.41	n. d.
13	0.15	1.70	90.20	6.08	0.30

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Lime-slaking.—The subject of lime-slaking has always been a matter of importance in connection with the ordinary use of lime in making mortar for structural work. During the past few years, however, it has assumed a far greater importance as being an essential part of the manufacture of "hydrated lime" and "lime-sand bricks." The theoretical aspects of the slaking of lime will be discussed in the section below, while the discussion of the actual methods of slaking will be found on pages 123–125 and in the two succeeding chapters (IX and X), which deal with the manufacture and properties of hydrated lime and of lime-sand brick respectively.

If water be poured upon a lump of pure quicklime, lime hydrate will be formed, while considerable heat will be evolved, the lime will expand notable in bulk, and the lump will fall into powder. The chem-

ical combination that takes place during this operation is represented in a formula by

$$\underset{\text{(Lime)}}{CaO} + \underset{\text{(Water)}}{H_2O} = \underset{\text{(Lime hydrate)}}{CaO_2H_2}.$$

With absolutely pure lime the amount of water that must be added in order to change all of the quicklime into lime hydrate will equal 32.1 per cent, by weight, of the quicklime. The resulting lime hydrate will therefore consist of 75.7 per cent lime (oxide) and 24.3 per cent water. Lime hydrate is a fine white powder, with a specific gravity of 2.078.

Effect of impurities present.—The above percentages would only hold true in case the burned lumps consisted entirely of quicklime (CaO). Actually we know that this theoretical purity is never attainable on a commercial scale. The original limestone always contains silica, alumina, iron oxide, etc., in quantities more or less large. The limestone is, moreover, never perfectly burned, so that some portions of unburned lime carbonate will always be present in the product.

The presence of these impurities, including silica, alumina, iron oxide, and fragments of unburned lime carbonate, operates to reduce the amount of water theoretically required for perfect slaking of the lime. For example, a perfectly pure lump of quicklime 100 lbs. in weight would require 32.1 lbs. of water for complete slaking. If the lump contained 10 per cent of impurities, however, it would require only 28.9 lbs. of water.

Expansion of volume.—The impurities also serve to reduce the expansion of volume which the lime would otherwise show. A pure lime, if slaked by adding the entire quantity of water at once, may increase $3\frac{1}{2}$ times in volume; if slaked gradually, only part of the water being added at a time, it will increase much less; while if allowed to air-slake its increase in volume will be only about 1.7 times its original volume. An impure lime, as above noted, will show less expansion, the difference being in direct ratio to the percentage of impurities.

The rapidity and intensity of the slaking will also be less with an impure than with a pure lime, and the amount of heat evolved during slaking will be decreased.

Effect of the presence of magnesia.—If the lime contain any considerable percentage of magnesia, slaking will take place more slowly and with less evolution of heat, while the expansion of volume will be less. In consequence of the slowness of the slaking more care is necessary with magnesian than with high-calcium limes in order to insure that the product has been thoroughly slaked.

Methods of slaking lime in ordinary practice.—When lime is used for making ordinary building-mortar, the common practice is to add much more than the amount of water theoretically required. The result is not only to slake the lime but to convert the slaked lime into a thin or thick paste, according to the amount of water used. When ordinary laborers are slaking lime it is evident that this method possesses the great advantage of being on the safe side. It is possible that the addition of the surplus water weakens the mortar somewhat, but on the other hand it insures thorough slaking, or would insure it if even reasonably good care were taken during the operation. The trouble, however, has been that lime-slaking is not regarded as an art, but as a disagreeable necessity, and it is usually carried on by laborers who are not even supposed to know anything about the subject.

The result of these conditions is that the slaked lime used in mortar rarely even approaches its theoretical efficiency. Either so much water has been added that the strength of the product is impaired or else the water-supply or mixing has been insufficient and the product is not thoroughly slaked.

A realization of these facts has caused the introduction of ready-slaked lime, prepared carefully at the lime-plants. This product is discussed in the following chapter under the head of " Hydrated lime." In its preparation particular care is given to insuring that the product shall be thoroughly slaked, and that this slaking shall be done with as little water as possible. Several distinct methods of slaking have accordingly been devised and are in use at different lime-hydrating plants.

In ordinary practice, where quicklime is slaked on the work, only one general method is followed, though books on construction invariably list and describe several other methods. The process as actually carried out is to form, on a plank floor or on a bed of sand, a circular wall of sand. The lime is shoveled into the ring thus formed and water is turned on from a hose until the laborer considers the amount sufficient. The lime commences to slake more or less quickly according to its composition, and when the process is completed it is covered over with a thin layer of sand until required for mortar.

Use of lime mortars.—Lime is never used alone as a binding material, for it shrinks greatly on drying and hardening, and this shrinkage would produce cracks if nothing were added to the mortar to counteract it. In practice sand is always added to lime mortars, the proportions for ordinary use being from two to four parts sand to one part lime paste.

The hardening of lime mortars is a simple process, though occasionally statements of opposite tenor may be found in print. It may be accepted as proven that lime mortars harden by simple recarbonation, the lime gradually absorbing carbon dioxide from the atmosphere and becoming, in fact, artificial limestones. As this absorption can take place only on the surface of the masonry, the lime mortar in the interior of a wall never becomes properly hardened. In this process the sand of the mortar takes no active part. It is merely an inert material, added solely in order to prevent shrinkage and consequent cracking. In this connection the reader may be referred to a discussion on pages 134–136 of the theory of lime-sand brick manufacture.

Strength of lime mortars.—Few recent determinations have been made on this point, as lime is steadily decreasing in importance as an engineering material.

The following tests, made by Mr. George S. Mills of Toledo, Ohio, have been recently published.* They are directly related to the point under discussion and furnish strong evidence of the superiority of the highly magnesian limes.

The limes tested were made by burning limestones of the following composition:

Constituents.	Magnesian.	High Calcium.
Silica (SiO_2)	0.45	n. d.
Alumina (Al_2O_3) } Iron oxide (Fe_2O_3)	0.28	n. d.
Lime carbonate ($CaCO_3$)	54.20	86.22
Magnesium carbonate ($MgCO_3$)	45.06	9.27

The limes resulting from burning the above limestones were slaked, mixed with sand in the proportion of one part slaked lime to two parts sand by weight, and made into briquettes, which were tested at various ages, with the results shown below. The figures given are in pounds per square inch and each value represents the average of the tests of from four to six briquettes.

In 1895 a series of experiments † on the strength of lime mortars was made by L. C. Sabin in connection with work on the Saulte Ste. Marie canal. The results of these tests are given in Table 44, below.

* Rhines, G. V. Tensile strength of high-calcium and magnesium limes. Municipal Engineering, vol. 28, pp. 4–7. Jan., 1905.

† Report of the Chief of Engineers, U. S. A., for 1896, pt. 5, p. 2839. 1896.

TABLE 43.

TENSILE STRENGTH OF MAGNESIAN AND HIGH-CALCIUM LIMES. (MILLS.)

Age.	High-calcium Lime.	Magnesian Lime.
4 weeks	30⅜	
8 "	36⅜	28⅝
3 months	39¼	37⅛
3 "	39	51
6 "	50⅝	83
1 year	44⅜	92⅝

In preparing the lime 120 lbs. of water was added to 40 lbs. quicklime, and after a few days the excess water was poured off and the paste passed through a 10-mesh sieve to remove lumps. In the original tables the percentages of lime and water in the various lime pastes are given. In the following table, however, this has been omitted, and the ratio given is that between the sand and the dry quicklime.

TABLE 44.

STRENGTH OF LIME MORTARS. (SABIN.)

Composition, Parts by Weight.		Kind of Sand.	Age.	No. of Tests.	Tensile Strength, Pounds per Square Inch.		
Lime	Sand.				Maximum.	Minimum.	Average.
1	3	Standard	28 days	5	58	26	46
1	6	"	"	5	69	50	62
1	8.8	"	"	5	62	37	47
1	8.8	Natural, passing 10-mesh	"	5	68	60	63
1	11.8	Standard	"	5	54	30	39
1	17.7	"	"	5	32	8	20
1	3	Crushed limestone	29 days	5	50	24	37
1	6	Screened, 20–40 mesh	"	5	66	38	51
1	8.8	" 20–40 "	"	5	76	55	64
1	8.8	Natural, passing 10-mesh	"	5	66	54	59
1	11.8	Screened, 20–40 mesh	"	5	68	52	56
1	17.7	" 20–40 "	"	5	48	40	43
1	3	Standard	3 months	5	52	42	47
1	3	Crushed limestone	"	5	64	20	51
1	6	Standard	"	5	59	40	47
1	6	Screened, 20–40 mesh	"	5	63	43	56
1	8.8	Standard	"	5	60	46	52
1	8.8	Screened, 20–40 mesh	"	5	78	67	71
1	8.8	Natural, passing 10-mesh	"	5	87	58	67
1	8.8	" " "	"	5	74	56	66
1	11.8	Standard	"	4	63	39	47
1	11.8	Screened, 20–40 mesh	.....	5	64	46	55
1	17.7	Standard	.....	4	40	34	36
1	17.7	Screened, 20–40 mesh	.....	5	41	38	39

CHAPTER IX.

HYDRATED LIME: ITS PREPARATION AND PROPERTIES.

In the preceding chapter it has been stated that quicklime (CaO) combines with about one-third of its own weight of water to form slaked or hydrated lime (CaH_2O_2). It has been further stated that lime-slaking when done on construction work by ordinary laborers is very inefficiently accomplished. This has always been realized, but it has only been within the past few years that any extensive effort has been made to provide a more satisfactory article for the contractor or builder.

Under the names of "new-process lime," "hydrated lime," "limoid," etc., a large number of lime-plants have within recent years placed a ready-slaked lime on the market. When this product is carefully prepared, it does away with all the trouble, waste, and unsatisfactory results entailed by the old method of slaking lump lime on the work. It seems probable, therefore, that increased knowledge of its valuable properties and increased care in its preparation will result in a great extension of its production and a corresponding decrease in the amount of lime marketed in the unhydrated form.

Preparation of hydrated lime.—In preparing hydrated lime on a commercial scale three stages of manufacture are necessary. These are:

(1) The lump quicklime must be ground to a fairly uniform small size.

(2) The powder or grains resulting must be thoroughly mixed with sufficient water.

(3) The slaked lime must finally be sieved or otherwise brought to a uniform fine powder.

Numberless patents have been issued to cover one or more of the points above named, but the general stages are the same in all. These will now be taken up separately and briefly discussed.

Grinding the quicklime.—Though grinding is practiced at most lime-hydrate plants, great variation exists in the extent to which it is carried. In some plants the quicklime is simply crushed to, say, ½ inch or 1 inch size, while in others the grinding is much finer. At a recently installed plant using the Dodge process, the quicklime passes first through a

small crusher, which reduces it to about ½ inch. The product is then fed to Sturtevant rock-emery mills, which reduce it so that about 80 per cent will pass a 50-mesh sieve.

A new rotary fine crusher, devised by the Sturtevant Mill Company, has also been used for crushing hydrated lime to ½ inch or so. The following details regarding this crusher are taken from a recent catalogue.

TABLE 43.

SIZES, CAPACITY, ETC., OF STURTEVANT CRUSHER.

Number.	Hopper Opening, Inches.	Approximate Capacity, Tons per Hour.	Approximate Horse-power.	Speed, Revolutions.	Pulley Diameter, Face.	Approximate Weight, Pounds.	Length.	Width.	Height.
1	13×18	2 to 6	6 to 10	300	24× 8	4000	6′ 6″	3′ 2″	5′ 8″
2	20×30	8 to 15	15 to 20	250	32×12	7500	8′ 2″	4′ 2″	6′ 10″

Mixing with water.—The next step is the actual slaking, and here considerable differences of practice appear, depending partly on what

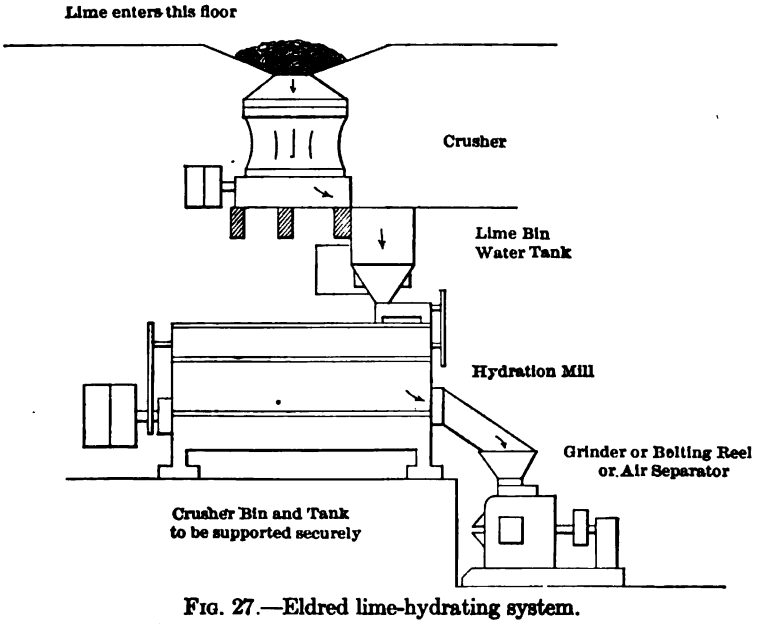

FIG. 27.—Eldred lime-hydrating system.

particular type of process is followed. The mixing is commonly carried on in a pan with agitators, similar to a familiar form of concrete mixer, or in a horizontal cylinder. All the lime may be added

to the water at once, or part may first be mixed with an excess of water and then the remainder of the lime added. In the well-known Dodge process the first plan is followed. In the Eldred process (U. S. Patent 721,871), in which the second plan is followed, the average amount of lime handled at one slaking is half a ton (1000 lbs.). Of this amount about 400 lbs. is first mixed and slaked with 450 to 500 lbs. water, and then the remaining 600 lbs. of quicklime is added to the resulting paste. A slaking-pan of the Walker & Elliott type is used.

The Campbell hydrater, shown in Fig. 28, has been successfully used at several lime-hydrating plants. The following data on its size, capacity, power, etc., are taken from a recent catalogue of the Clyde Iron Works.

TABLE 46.

CAPACITY, POWER, ETC., OF CAMPBELL LIME-HYDRATER.

No.	Diameter of Pan.	Height of Pan.	Capacity per Batch.	Pulley	Speed, R. P. M.	Weight.
2	6 ft. 0 in.	16 in.	1000 lbs.	6×24 in.	175	4500 lbs.
3	10 " 6 "	20 "	2000 "	6×24 "	175	6800 "

The amount of water used will vary with the character of the lime. If it is a pure high-calcium lime, more water is added than if it contains any considerable percentage of either magnesia or clayey matter. In one process, for example, 55 lbs. of water is added to each 100 lbs. of high-calcium lime, or 30 lbs. water to 100 lbs. magnesian lime.

Sieving the product.—After slaking the product is usually stored in bins for forty-eight hours or so, after which it is ready for use. Before packing, however, the coarser particles are removed either by screening or through use of an air-separating device. When screens are used, a 50-mesh is the common grade, the pitch of the screen surface being changed to obtain whatever fineness is required. The Jeffrey Columbian Separator, which has been used for this purpose, is described in the table below.

TABLE 47.

DETAILS OF JEFFREY SEPARATOR.

Number of Machine.	Width Over All.	Length Over All.	Height Over All.	Size of Main Driving Pulley.	Speed of Main Driving Pulley.	Size of Screening Surface.
0	7 ft. 3½ in.	6 ft. 11¼ in.	7 ft.	12 in.×4 in.	250 rev.	4 ft.×6 ft.
2	11 " 3½ in.	6 " 11¼ "	7 "	12 " ×4 "	250 "	4 " ×6 "

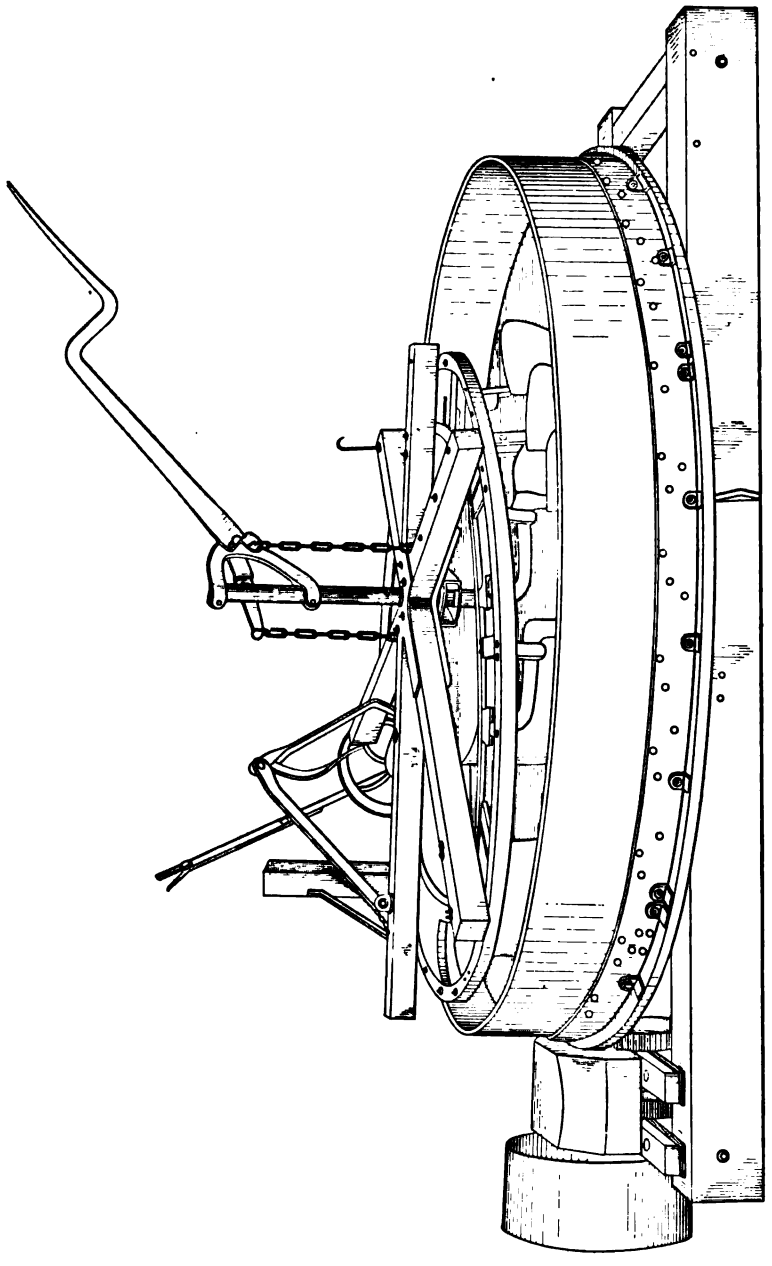

FIG. 28.—Campbell lime-hydrater. (Clyde Iron Works.)

STANDARDS FOR PACKING, ETC.—At a meeting of the hydrated-lime manufacturers of the United States, held in July, 1904, the following standards for packing and selling the product were adopted.*

Bags.—A heavy, closely woven burlap or duck bag, containing 100 lbs., 20 bags to the ton. A paper bag containing 40 lbs., 50 bags to the ton.

Quotations.—All quotations are made including the cost of the package, no bulk quotations being made.

Returned sacks.—The burlap or duck bags will be repurchased from the customer at ten cents each when returned to the mill in good condition, freight prepaid.

Terms of settlement.—A discount of 1 per cent will be allowed for cash in ten days, the discount to be taken on the full price, including the bags. f. o. b. manufacturer's plant or shipping-point. Net cash thirty days.

COST OF EQUIPMENT.—The following estimate of cost of equipment, etc., has been furnished by Mr. B. E. Eldred:

Product per hour	5 tons	10 tons
Cost of plant and equipment	$8,000	$10,000
Men required for operation	4–5	6–8
Maximum power required	35 H.P.	50 H.P.
Average power throughout day	15 "	20 "

In estimating the cost of lime hydrating, it should be recollected that the product gains greatly in weight during the process. A ton of quicklime (2000 lbs.) will give from 2400 to 2600 lbs. hydrated lime.

Tests of hydrated lime.—The following tests of two kinds of hydrated lime, while made principally for the purposes of comparing high-calcium with magnesian limes, will serve to give an idea of the tensile strength of hydrated lime in general.

TABLE 48.

TENSILE STRENGTH OF MAGNESIAN AND NON-MAGNESIAN HYDRATED LIME.

Kind of Lime.	4 Weeks.	8 Weeks.	3 Months.	4 Months.	6 Months.
Magnesian lime	8 lbs.	17 lbs.	37⅛ lbs.	51 lbs.	83 lbs.
High-calcium lime	30⅔ "	36⅜ "	39¼ "	39 "	50⅝ "

Engineering News, vol. 51, p. 543. June 9, 1904.

The tests above quoted were made by Mr. S. T. Brigham on hydrated lime prepared by the Dodge process. The mortar in each case was composed of two parts by weight of sand to one part of slaked lime, and the results are given in pounds per square inch.

* Engineering News, vol. 52, p. 220, Sept. 8, 1904.

Mixture of hydrated lime and Portland cement.—Among the most interesting features of this new product are the results obtained by mixing slaked lime with Portland cement. This mixture has been tested by several experimenters, and the results of the tests are quoted and discussed both by Sabin and Thompson in their recent books on cements and concretes. The addition of hydrated lime to a Portland cement mortar renders it more plastic and easier to work. When this addition does not exceed 10 or 20 per cent an actual increase in tensile strength seems to be shown.

List of references on hydrated lime.

Brigham, S. T. The manufacture and properties of hydrate of lime. Engineering News, vol. 50, pp. 177–179. Aug. 27, 1903.

Brigham, S. T. Hydrated lime. Engineering News, vol. 51, pp. 543. June 9, 1904.

Peppel, S. V. Lime experiments. Rock Products, vol. 3, p. 1, p. 17. April, May, 1904.

Warner, C. Hydrated lime. Engineering News, vol. 50, pp. 320–321. Oct. 8, 1903.

Warner, C. Strength tests of mixtures of hydrated lime and Portland cement. Engineering News, vol. 50, p. 544. Dec. 17, 1903.

Warner, C. Standards adopted by manufacturers of hydrated lime. Engineering News, vol. 52, p. 220. Sept. 8, 1904.

Statistics of hydrated lime.—The following data from Mineral Resources U. S. will serve to give an idea of the growth of this particular form of lime:

TABLE 49.

HYDRATED LIME MANUFACTURED AND SOLD IN THE UNITED STATES, 1906–1920.

Year.	Quantity (Short Tons).	Value.	Average Price per Ton.	Number of Plants Reporting Operations.
1906	120,357	$479,079	$3.98	30
1907	140,135	657,636	4.69	33
1908	136,411	548,262	4.02	46
1909	204,611	904,900	4.43	50
1910	320,819	1,288,789	4.02	51
1911	304,593	1,372,057	4.50	60
1912	416,890	1,829,064	4.39	64
1913	493,269	2,205,657	4.47	80
1914	515,121	2,239,916	4.35	82
1915	581,114	2,457,602	4.23	84
1916	717,382	3,626,998	5.06	89
1917	709,157	4,643,004	6.55	90
1918	620,216	5,342,113	8.61	90
1919	777,408	7,061,146	9.08	93
1920	853,116	9,287,562	10.89	98

CHAPTER X.

MANUFACTURE AND PROPERTIES OF LIME-SAND BRICKS.

THE term lime-sand brick will be used in this volume to cover all bricks made by mixing sand or gravel with a relatively small percentage of slaked lime, pressing the mixture into form in a brick mold, and drying and hardening the product, either by sun-heat or artificial methods. The general process is not in any way patentable, being of very ancient date. Various details of the process may, however, be covered by valid patents, such, for example, as on the type of molding-press used, on the exact methods and appliances for drying and hardening, and on various more or less "secret" compounds which may be added to facilitate hardening or to increase the final strength of the product.

Early history of the industry.—Though in the past few years the "invention" of lime-sand brick has been heralded as a new matter, the general process has been employed for many years both in America and in Europe.

The following interesting contemporary account * of the manufacture and use of lime bricks in New Jersey in 1855 incidentally establishes the fact that the industry had been known near Philadelphia since 1838.

"*Gravel bricks.*—A new building material has been introduced in Cumberland and some of the adjoining counties which promises to be both cheap and durable. The common clean gravel and coarse sand of the country is mixed with one-twelfth its measure of stone lime and made into bricks. These bricks are sun-dried and then laid up into walls. They are cheap, durable, and but little affected by the changes of the seasons.

"In making, the gravel is laid on a common mortar bed, and the lime, which is slaked and made into a thin putty in a lime-trough, is then run on the gravel and the whole worked up into mortar. The

* Cook, G. W., in Second Ann. Rept. of the Geol. Surv. of the State of N. J. for the year 1855, pp. 107–108. 1856.

bricks are usually made as large as is convenient for handling and of dimensions to suit the work for which they are intended. The molds are made, several in the same frame, as deep as the thickness of the brick and without any bottom; they are set on smooth ground and filled with mortar. This is worked in a little with the shovel and struck off at the top. In ten or fifteen minutes the mortar will have set, so that the molds can be taken off. The bricks are soon dry enough to handle, when they can be piled up and allowed to dry thoroughly. They are laid in mortar similar to that from which the bricks are made, and the outside of the buildings are roughcast with the same.

"Several buildings of this kind have been erected in Bridgeton and its vicinity within the last eight or ten years, and in Norristown, Pa., it has been in use for seventeen years past. It has stood well, growing harder and more solid every year. The bricks have come to be a regular article of manufacture in several places. Those of $12'' \times 9'' \times 6''$ were selling in Bridgeton in 1855 for $20 a thousand, and they could be laid, and mortar found, for $10 a thousand, which is less than half the cost of the same measure of red-brick wall. The material of which these bricks are made being found almost everywhere, and the labor of making and laying them up being very simple, farmers, and others who have control of labor can make and lay them at times when the expense of the work would not be felt, and thus a saving much greater than that mentioned could be made. When first laid up they are not quite as strong as other bricks, and greater care is necessary in making a solid foundation, otherwise unequal settling and cracks in the walls will result. Care must be taken to make them so early in the season as to be entirely dry before the winter's frost."

It will be seen that the general process of lime-sand brick manufacture is well covered by the above description, and that both the merits and defects of the product are stated rather more frankly than is the practice among its advocates to-day. It is to be kept in mind, however, that the lime-sand brick manufacturers to-day claim that their product derives its hardness, not from a simple recarbonation of the lime, but from a more or less thorough combination of the lime with the silica of the sand or gravel. As this is a matter of interest and importance, it will be discussed in some detail on a later page.

Whatever the value of their contention may be, it is evident that even this improvement has been anticipated. That a "lime-silicate" brick of modern type was made about 1850 is proven by the following quotation of that date:

"Recent improvements in the manufacture of concrete building

blocks have so far perfected the product as to bring this stone into successful competition with the very best of the natural and artificial building materials. The action of lime upon silica, forming a silicate of lime (*calcmakit*), and thus binding together particles of sand, as in mortar, has been known from the remotest ages, and concrete walls of great antiquity are now standing, vying with the natural rock in hardness and durability. Some years since a concrete block, compacted by pressure, was brought out in this country and used to some extent as a building material, but the slowness of the induration and uncertainty in the product hindered its general introduction. The improvements referred to consist in the use of heat in connection with quicklime and sand, by which the formation of the silicate of lime is hastened, and the same effect, which formerly took years to be consummated, is now produced in a few days. Ground quicklime is thoroughly mixed with clean, sharp sand, and is then subjected to the action of either superheated or high-pressure steam, which slakes the lime and causes it to attack the silica. This process continues for from twenty minutes to ten days, according to the degree of heat employed, when the material is molded and compressed by a heavy steam-hammer into blocks of any desired form. The ordinary building-block made by this process is 10 inches wide and 4 inches deep, having a hollow space in the center 6 inches long by 1 inch broad; when the blocks are placed upon each other, so as to break joints, a continuous and connected series of air-chambers will be formed within the wall. Thirty days' exposure of the block, after it is first formed, to the air, produces an induration quite sufficient for all ordinary building purposes, but the block continues to harden for an unlimited period. A church built entirely of this material was recently dedicated at Morrisania. A number of fine buildings have already been constructed of this material in Chicago, among which may be mentioned a handsome block of dwellings on Sixteenth Street, and the Young Men's Christian Association of the same city, which was recently burned. The endurance of this stone when submitted to repeated freezing and thawing is quite remarkable, and experiment proves it to be equal in this respect to granite."

The theory of lime-sand brick.—When ordinary quicklime is slaked, mixed with sand, and used as mortar the mixture hardens very slowly and never attains much strength. The hardening is due to the fact that the slaked lime gradually absorbs carbon dioxide from the atmosphere and recarbonates, forming a sort of artificial limestone. So far as known, there is no chemical action between the lime and the

sand of the mortar, though occasionally the statement is made that with increasing age a certain amount of chemical action does take place, resulting in the formation of a certain percentage of lime silicate. This, however, is more than doubtful.

In making lime-sand brick by modern processes, it is claimed by its advocates that the lime and sand of the brick *do* combine to form lime silicates, the combination being in this case brought about through the action of steam under high pressure. It is also claimed, though rather by suggestion than by direct statement, that these lime silicates make up a considerable proportion of the entire mass of the brick.

To the present writer the first claim does not seem to be justified. No proofs have been presented that, in the course of lime-sand brick manufacture, any chemical combination takes place between the lime and the sand. It is undoubtedly true that the treatment with steam under pressure increases in some unexplained way the chemical activity of the slaked lime; but further than that we cannot go at present.

The second point, regarding the percentage of lime silicate which would be formed *if* chemical combination of lime and silica took place, can be readily settled. The lime and silica *might* unite in any one of three proportions, forming respectively the calcic silicate ($CaO \cdot SiO_2$), the dicalcic silicate ($2CaO \cdot SiO_2$), or the tricaclic silicate ($3CaO \cdot SiO_2$). The last of these is the one which is formed during the processes of manufacture of Portland cement, and is the hydraulic silicate *par excellence*. In most sand-lime brick literature a similarity between that product and Portland cement is suggested, even if not definitely claimed. In the little table below the percentage composition of these three lime silicates is presented. It will be seen that the tricalcic silicate contains 73.59 per cent lime to 26.41 per cent silica, while the proportion of lime decreases until it reaches 51.84 per cent in the unicalcic silicate.

TABLE 50.

PERCENTAGE COMPOSITION OF VARIOUS LIME SILICATES.

Compound.	Per Cent CaO.	Per Cent SiO_2.
$CaO\ SiO_2$.....	51.84	48.16
$2CaO \cdot SiO_2$.....	65.01	34.99
$3CaO \cdot SiO_2$.....	73.59	26.41

The bearing of these facts upon lime-sand brick manufacture is obvious enough.

The amount of slaked lime used in making lime-sand brick will amount to 5 to 10 per cent of the whole mass, averaging about 8 per cent. If *all* of this 8 per cent of lime be combined with silica in the richest possible silicate ($CaO \cdot SiO_2$), it will take up only 7 per cent of sand. So that on the most hopeful possible basis only 15 per cent of the brick would have any binding properties, the remainder being merely uncombined and inert sand.

General processes of lime-sand brick manufacture.—The general processes involved in the manufacture of lime-sand brick are, in order, as follows:

a. Slaking the lime.
b. Mixing the lime and sand.
c. Pressing the mixture into molds.
d. Hardening the brick.

Necessary properties of the sand.—All the sand should pass a 20-mesh screen, and it is desirable that part of it (say 10 per cent) should be fine enough to pass a 150-mesh screen. Clayey material in the sand is detrimental to the strength of the brick made from it. The composition of the sand grains themselves probably has little influence on the *strength* of the resulting brick; but in order to secure a light and uniform color it is desirable that the sand should consist almost entirely of grains of quartz and that the dark silicate minerals (hornblende garnet, mica, etc.) should be present in no great quantity.

In testing the influence of size of sand, Peppel * used mixtures in various proportions of two sands. These gave the following results on sieving:

	Coarse Sand.	Fine Sand.
20- to 40-mesh.....	50 per cent	
40- " 60- "	33 " "	
60- " 80- "	7 " "	
80- " 100- "	7 " "	
100- " 120- "	2 " "	$\frac{7}{10}$ per cent
120- " 150- "	1 " "	1 " "
150- " 200- "	.....	$1\frac{1}{4}$ " "
Passing 200-mesh.....	.....	$93\frac{1}{20}$ " "

The coarse sand was a very pure sharp glass sand; the fine sand was crushed quartz. Made up into bricks with 5 per cent of lime the results shown in the following table were obtained.

* Trans. Amer. Ceramic Soc., vol. 5, page 4 of pamphlet edition.

TABLE 51.

EFFECT OF FINENESS OF SAND. (PEPPEL.)

Composition of Sand Mixture by Parts.		Crushing Strength, Pounds per Square Inch.	Tensile Strength, Pounds per Square Inch.
Coarse.	Fine.		
8	2	3114	131
4	2	2955	144
3	2	2461	224

These tests show that the bricks decrease in compressive strength and increase in tensile strength as the amount of fine sand in the mixture increases. These results of themselves appear to be unfavorable to the contention of lime-sand brick manufacturers, that the strength of their product is due to chemical reactions between the sand and the lime. For if this contention were true, the finer sand particles would certainly be more active chemically than the coarser grains, and an increase in fineness of sand would necessarily mean more extensive chemical interaction and consequently greater strength in *both* compression and tension.

Drying the sand.—In order to secure uniformity in the product it is desirable that the sand should be dried before mixing with the lime. So far this point has not been realized by many manufacturers, who are content to use the sand as it comes from the pit—at one time practically dry, at another carrying 10 to 15 per cent of moisture.

As to methods of sand-drying, considerable differences in practice exist. In the Schwarz machine, described and figured on page 139, the sand is placed in a steam-jacketed drum, the drying being aided by revolving paddles which stir up the sand. At a number of plants live or exhaust steam is used in pipe-dryers, the sand being shoveled on a series of horizontal pipes filled with steam. The best practice is probably to use a rotary dryer. At one plant * a direct-heat rotary dryer 22 inches in diameter and 22 feet long, set at a slope of about $\frac{1}{4}$ inch to the foot, dries 40 to 50 yards of sand in ten hours with a fuel consumption of 700 lbs. coal. At another, a 30-foot dryer set at a slope of about $\frac{1}{8}$ inch per foot, with a fan to induce draft, is handling 40 to 50 yards sand in ten hours with a consumption of 600 to 800 lbs. coal.

Necessary properties of the lime.—The lime should be carefully and thoroughly slaked, and should be as free from impurities as possible. The presence of more than a few per cent of clayey matter or iron oxide

* The Clay Worker, vol. 42, p. 588. 1904.

is undesirable, not so much because of its effect on the strength or durability of the brick as because of its effect on the color.

The following experiments on high-calcium *vs.* magnesian limes appear to prove that the latter give bricks inferior in strength. In view of the results attained elsewhere, however, those in the table below should be accepted with caution.

TABLE 52.

COMPARATIVE TESTS OF HIGH-CALCIUM AND MAGNESIAN LIME BRICKS. (PEPPEL.)

Lime Used.	Amount.	Tests of Strength.				Per Cent of Water Absorbed.
		After Hardening.		After Freezing.		
		Compression, Pounds per Square Inch.	Tension, Pounds per Square Inch.	Compression, Pounds per Square Inch.	Tension, Pounds per Square Inch.	
High-calcium.....	.....	7745	437	9007	371	8.62
Magnesian.....	.....	5187	286	5853	314	9.11

Trans. Amer. Ceramic Soc., vol. 5, page 15 of pamphlet edition.

The lime-sand bricks whose results are shown in the above table were made up of two parts coarse sand and one part fine sand, to which base was added 10 per cent of lime. The blocks were molded under a pressure of 15,000 lbs. per square inch and hardened by exposure for four to fourteen hours to a steam pressure of 150 lbs. per square inch at a temperature of 185° C. Each of the results given in the table is the average of twelve tests.

Methods of slaking the lime.—The lime may be either slaked to a paste by the addition of more water than is theoretically required or slaked to a dry powder. The general methods employed are usually similar to those in the lime-hydrate industry. In one process, however, a machine of entirely different type is employed, which requires some notice.

The Schwarz process is described * as follows:

"The first operation in the Schwarz process is the mixing of the sand and lime, which is done in a vacuum mixing-machine. This machine is shown in transverse and longitudinal section in Fig. 29. Briefly described, the machine consists of a steam-jacketed drum with interior rotary blades operated by suitable gearing outside and at one

* Engineering News, vol. 49, p. 179. Feb. 19, 1903.

end. This drum, which has a capacity of about three tons of sand, is filled by means of a funnel placed above it. When the drum is charged, the interior mixing-blades are set in motion and the contents are heated by means of the steam-jacket surrounding the drum. A vacuum pump attached to the apparatus removes the steam and air from the drum. When the sand has been properly dried the required

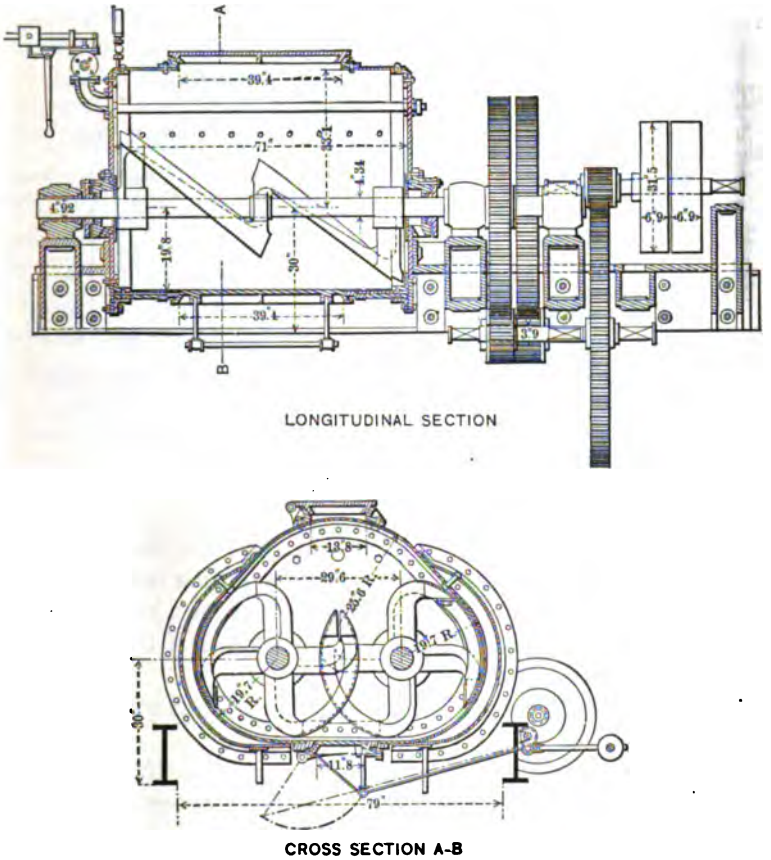

FIG. 29.—Schwarz drying- and mixing-machine.

quantity of finely pulverized lime is introduced into the drum through a special aperture and the mixture is again stirred and heated. The necessary quantity of moisture is then introduced into the drum in the form of water or steam by means of a pipe penetrating the interior of the drum. After wetting, the mixture continues to be stirred and heated during a sufficient time to allow a preliminary combination of

the lime and sand to take place and produce a mixture with sufficient tenacity to permit of easy molding."

Proportions of mixtures.—The slaked lime is mixed with sand in the usual proportion of 5 to 10 lbs. of lime to 100 lbs. of sand. Peppel experimented on this point by preparing mixtures carrying various proportions of lime and sand. His results are shown in the following table:

TABLE 53.

EFFECT OF PERCENTAGE OF LIME. (PEPPEL.)

Composition of Mixture.			Strength in Pounds per Square Inch.					
			After Hardening.		After Aging.		After Freezing.	
Coarse. Sand.	Fine Sand.	Lime.	Compression.	Tension.	Compression.	Tension.	Compression.	Tension.
60 lbs.	40 lbs.	5 lbs. magnesian lime....	3697	427	.....	.....	3812	
60 "	40 "	10 " " "	5607	503	5843	446	7525	417
60 "	40 "	5 lbs. high-calcium lime..	2636	194				
60 "	40 "	40 " " " ..	7018	541	7153	622	7995	516

Trans. Amer. Ceramic. Soc., vol. 5, page 13 of pamphlet edition.

The mixture may be accomplished in pug-mills, edge-runner mills, wet pans or dry pans.

Methods of molding.—The mixture is shaped into bricks in a press. Peppel states * that a press should fulfil the following requirements:

" (1) The press must be able to regularly deliver a pressure of from 200 to 250 tons per brick and yet not break down if by accident the pressure rises somewhat higher.

" (2) The filling of the mold must be accomplished with great accuracy and uniformity.

" (3) All working parts must be so arranged that they will be free from contact with loose sand, otherwise they will cut out at an alarming rate.

" (4) The dies and mold linings must be made of the hardest material obtainable."

Many presses, both of American and German design, are now on the market for use in the lime-sand brick industry. Any machine that will press clay brick has power and strength enough to handle lime-sand brick, but the new product is so fragile as to require delicate handling in taking off the press.

* Trans. American Ceramic Society, vol. 5, pp. 33–35 of pamphlet edition.

Methods of hardening the bricks.—Three general types of hardening processes have been in use. These are: (1) hardening by simple exposure to the atmosphere; (2) hardening in an atmosphere saturated with carbon dioxide; (3) hardening in a cylinder filled with steam under pressure.

The first of these processes is slow, since the hardening takes place only as rapidly as the lime in the brick can absorb water and carbon dioxide from the atmosphere. The second process is more rapid, but the change of slaked lime to lime carbonate is still incomplete. In the third process, which is the one used at practically all lime-sand brick plants to-day, the reactions are rapid, and its advocates claim in addition that the steam under pressure causes the combination of the lime with the sand, so as to form a greater or lesser amount of silicate of lime.

In the process as now followed, the bricks are loaded onto trucks and these are run into a long horizontal cylinder. This hardening cylinder is then closed and steam under pressure is admitted.

The experiments, whose results are given in table 54 were undertaken by S. V. Peppel to determine the most advantageous steam pressure and time of hardening. In discussing these results, Peppel states that "this table shows that four hours' time at 150 lbs. steam pressure is sufficient; that six or eight hours are required at 120 lbs.; that eight to twelve hours are required at 100 lbs."

TABLE 54.

EFFECTS OF STEAM PRESSURE AND TIME OF HARDENING. (PEPPEL.)
Strength in pounds per square inch.

Steam Pressure, Pounds per Square Inch.	Hours in Steam.	A.		B.		C.		D.		E.	
		Compression.	Tension.	Compression.	Tension.	Compression.	Tension.	Compression.	Tension.	Compression.	Tension.
150	4	7896	544	5303	392	5282	591	4514	470	4441	330
150	6	7994	390	5045	199						
150	8	7404	509	4957	262	6170	632	4249	430	4491	337
150	10	7767	464	4902	284						
150	12	7514	337	5064	250	6165	556	4543	434	4924	349
150	14	7894	380	5849	329						
120	4	6989	.....	5989	.....	5403	.....	4300	.....	5760	
120	6	7063	.....	6495							
120	8	8545	.....	6038	.....	5868	.....	5142	.....	6718	
100	4	6385	.....	5921	.....	4280	.....	4048	.....	4588	
100	6	7566	.....	6507	.....	5564	.....	4456	.....	6544	
100	8	7494	.....	5753							

Trans. Amer. Ceramic Soc., vol. 5, page 25 of pamphlet edition.

The hardening cylinder, according to Peppel, should be constructed of $\frac{5}{8}$ to $\frac{3}{4}$-inch iron or steel plate. The cylinder is bricked in to prevent radiation and has one removable end or head. This head "should be handled by an overhead crane or a block and tackle. Hinged doors with a wheel on the bottom and a track for the wheel to run on have been used. These are clumsy affairs to move and occupy much space, and should never be recommended. The bolts should be so fastened to the cylinder that the head can readily be swung into place. These bolts are usually $1\frac{1}{4}$ to $1\frac{1}{2}$ inches in diameter." The cylinder varies in length from 35 to 67 feet, and in diameter, from $5\frac{1}{2}$ to 7 feet.

Costs of plant and manufacture.—The following estimates of cost of plant and production are given by Peppel:*

COST OF PLANT FOR 40,000 BRICK PER DAY. (PEPPEL.)

Land and buildings	$15,000
1 wet-pan	1,000
1 ball-mill	500
2 presses	4,400
2 pug-mills	800
Conveyors	6,000
Shafting and belting	3,000
1 100-H.P. Corliss engine	2,500
2 100-H.P. boilers	2,000
1 25-H.P. boiler	300
4 hardening-cylinders 7′×60′	8,000
Erecting and insulating cylinders	1,000
Pipes for preliminary heating	1,000
Railroad tracks, etc	4,500
	$50,000

COST OF MANUFACTURE, 40,000 BRICK. (PEPPEL.)

Sand: 157 cubic yards at $0.07	$ 11.00
Lime: 11 tons at $4.00	44.00
Coal: 3 tons at $2.25	6.75
Repairs	5.00
Oil and grease	3.00
Labor: 40 men at $1.35	54.00
Foreman at $2.50	2.50
Office expenses	20.00
Depreciation and interest, 12 per cent	20.00
	$166.25
Selling expenses, 10 per cent	16.00
	$182.25
Cost of brick per thousand	$4.55

* Trans. Amer. Ceramic Soc., vol. 4.

With these estimates may be compared the following data on costs of production, gathered from various sources:

The Huennekes Company, in advertising their system of lime-sand brick manufacture, state that an output of 20,000 brick per day of twenty-four hours will require

Labor:
- 1 engineer
- 1 fireman
- 8 laborers

Material:
- 3 tons coal
- 2½ tons lime
- 50 tons sand

At a small plant using another system recently visited by the writer, six men operated the mill, exclusive of superintendence. They were distributed as follows: two digging and handling sand, one at the mixer, two at the press, and one at the engine. A 30-H.P. engine sufficed to run two pan-mixers, two screw-mixers, one elevator, and one brick-press, and gave a product of 10,000 brick per day of twenty-four hours. Sand-beds occur near the plant, but lime is expensive, being bought in the hydrate form and carried by rail for over 400 miles. Coal is also expensive. Neither labor nor machinery is particularly efficient, and repairs and supplies must therefore be allowed for at rather a high figure. The finished brick are not of very good grade, but can be sold in absence of competition from a really good clay brick at $8.00 to $9.00 per thousand.

The following is probably a fair estimate of the cost of manufacturing lime-sand brick at this plant:

Lime, 1½ tons at $8.00 per ton	$12.00
Coal, 1½ tons at $4.25 per ton	6.38
Labor, 6 men	8.75
Superintendence and office expenses	10.00
Repairs, supplies, etc	2.00
Interest, depreciation, etc	6.00
Cost per 10,000 brick	$45.13
Cost per thousand	4.51

At a recent convention * of sand-lime brick manufacturers, several partial estimates of cost of manufacture were submitted. One estimate put the total cost of manufacture at $5.00 per thousand brick, allowing for coal at $4.25 per ton, lime at 80 cents per barrel, and sand

* Proceedings of the 1st Annual Convention, National Assoc. Mfrs. Sand-Lime Products, reported in the "Clay Worker," vol. 42, pp. 582–591. Dec., 1904.

at 60 cents per yard. Another placed the total cost at $3.60 per thousand, with slack coal at $1.45 per ton and lime at 40 cents per barrel. A third, slightly more detailed, gave the following figures for a plant of 15,000 capacity.

Sand and lime	$1.10
Labor	1.75
Fuel and repairs	0.50
Fixed charges	1.00
Total cost per thousand	$4.35

All of the costs above stated are based on unit prices which have since advanced greatly. For use at present, or in future years, the results should be corrected by use of the index numbers given on pages 6–8 of this volume.

Composition of lime-sand bricks.—Lime-sand bricks will usually range in composition between the following limits:

Silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3)	85–95 per cent
Lime (CaO) and magnesia (MgO)	9– 3 " "
Water	6– 2 " "

The bulk composition of the product is therefore a fairly definite matter and not subject to discussion. The point concerning which there is a definite disagreement is as to the manner in which the above constituents are combined in the brick. The more ardent advocates of lime-sand brick claim that most of the lime is combined with part of the silica as a calcium silicate, and support this contention by presenting analyses showing the presence of noticeabl epercentages of soluble silica. In the opinion of the present writer this contention is not proven.

Physical properties of lime-sand bricks.—Lime-sand bricks are sufficiently strong, when subjected to direct compressive strains, for all ordinary structural purposes. Many of them, however, are very fragile and require careful handling both in transportation and on the work.

The following comparison has been made * by Peppel between lime-sand bricks and a series of natural sandstones tested by the Wisconsin Geological Survey.

TABLE 55.

LIME-SAND BRICKS *vs.* NATURAL SANDSTONE. (PEPPEL.)

	Lime-sand Bricks.	Natural Sandstone.
Weight per cubic foot	136 lbs.	137 lbs.
Absorption	8 per cent	7.3 per cent
Crushing strength per sq. in	7745 lbs.	6535 lbs.
Coefficient of elasticity	600,000	165,440

* Trans. Amer. Ceramic Society, vol. 5, p. 31 of pamphlet edition.

The following series of tests show much lower compressive strength and higher absorption than those above quoted.

The tests summarized in the following table were made in 1901 on lime-sand bricks made on the Huennekes system.

TABLE 56.

PHYSICAL TESTS OF LIME-SAND BRICK. (PITTSBURGH TESTING LABORATORY.)

Crushing Strength per Square Inch.	Absorption Test 45 Hours in Water. Per Cent Gain.	Absorption after Freezing Test. Per Cent Gain.	Crushing Strength per Square Inch after Freezing.
3518 lbs.	11.6	12.4	4137 lbs.
4162 "	8.57	8.8	5202 "
3859 "	11.3	11.4	

In making the absorption tests half bricks were used, which were dried thoroughly before being immersed in water. After remaining in water 45 hours, bricks were frozen 4 hours at a temperature of 14° F., then thawed in warm water 12 hours, frozen again at a temperature of 9° F. for a period of 3½ hours, thawed in hot water 3 hours, frozen at a temperature of 12° F. for 3½ hours, and finally thawed in hot water for 12 hours. Final absorption test made and then bricks were again thoroughly dried. Bricks showed no signs of cracking or disintegration.

Another series of tests of brick made by the Ventnor Concrete Co. operating on the Huennekes system, is summarized below.

TABLE 57.

TESTS OF LIME-SAND BRICKS. (U. S. NAVAL ACADEMY.)

Crushing: Size of cube 2″×2″×2$\frac{5}{16}$″.

	Total.	Per Sq. In.
No. 1	12,580 lbs.	3145 lbs.
No. 2	16,500 "	4125 "
No. 3	10,350 "	2588 "

Absorption: Immersed 72 hours.

	Weight in Grains.			
	Dry.	Wet.	Difference.	Per Cent.
No. 1	1241	1337	96	7.735
No. 2	1270	1375	105	2.275
No. 3	1300	1498	108	7.777

Approximate size of whole brick ..... 8$\frac{3}{8}$″×4$\frac{1}{2}$″×2$\frac{13}{16}$″

Approximate weight of whole brick ..... 5 lbs. 14 ounces

One whole brick and one brick broken in four pieces were soaked in warm water and then put in tin cans with sufficient water to cover

them and frozen in the open air, the thermometer ranging from 4 degrees to 20 above zero. This was repeated four times, thawing in warm water each time. They were then frozen in salt and ice (temperature being above freezing-point) three times. The entire process did not have any bad results with the whole brick. The pieces scaled a little at the edges, probably due to small pieces loosened by the breaking of the brick. Another brick was placed in open air in a freezing temperature and water allowed to drip and freeze on it until coated with ice without any bad results.

Two specimens of lime-sand brick (Huennekes system) were tested in 1904 by Prof. Marston, giving compressive strengths respectively of 3210 and 2097 lbs. per square inch, and absorptions of 10.9 and 11.0 per cent.

In 1904 Prof. Woolson tested several lime-sand brick made on the Schwarz system, with the following results.

TABLE 58.

COMPRESSION TESTS, LIME-SAND BRICK. (WOOLSON.)

	(*a*)	(*b*)
Height, inches	2.25	2.40
Width, inches	4.13	4.15
Thickness, inches	4.00	4.00
Area, square inches	16.52	16.60
Maximum load, lbs.	59,340	60,300
Ultimate strength, lbs. per sq. in.	3,592	3,633

In Table 59 are given the results of a series of tests made at Charlottenburg on various brands of lime-sand brick made in Germany. It will be seen that these results are very low.

TABLE 59.

PHYSICAL TESTS OF LIME-SAND BRICKS. (CHARLOTTENBURG.)

Crushing Strength in Pounds per Square Inch.			Absorption, Per Cent.
Dry Brick.	Water-soaked Brick.	After Freezing.	
1704	1903	2229	12.0
2215	2073	2300	14.0
4189	3933	4260	9.0
1732	1846	2187	10.6
3710	....	3238	
850	....	1335	
1353	....	1747	
1193	1335	1562	18.3

Trans. Amer. Ceramic Soc., vol. 1.

Summary of the results of tests.—The three American series of tests above quoted (Tables 56, 57, and 58) were made on samples of brick furnished by the manufacturers, and the results of these tests are now used for advertising purposes. It seems fair to assume, therefore, that these results are not inferior to the average run, but are, on the contrary, probably better than the usual American lime-sand brick as found on the market.

The bricks tested at Charlottenburg, on the other hand, were probably selected from marketed products, and are probably fairly representative of the average German product as it reaches the building trade.

The two sets of results have therefore been averaged separately with the results given below.

TABLE 60.

SUMMARY OF LIME-SAND BRICK TESTS.

	Strength, Pounds per Sq. In.			Absorption, Per Cent.		
	Max.	Min.	Average.	Max.	Min.	Average.
Average 10 American tests.....	4162	2097	3393	12.4	2.275	8.89
Average 8 German tests.....	4189	850	2118	18.3	9.0	12.78

Comparison with clay brick.—It will be of interest to compare with these the results of a series of tests recently published,* which were made in 1903 by Prof. Woolson on an extensive series of clay bricks. The bricks were all made in New Jersey, and were fair average samples, taken from stock piles. For convenience of reference the bricks have been divided into two classes—front brick and common brick—and the two classes are separately averaged in the following table.

TABLE 61.

SUMMARY OF CLAY-BRICK TESTS. (WOOLSON.)

	Compressive Strength, Pounds per Square Inch.			Absorption, Per Cent.		
	Max.	Min.	Average.	Max.	Min.	Average.
Front brick.....	13,873	5583	8805	8.61	1.34	4.20
Common brick.....	11,058	661	3785	15.38	6.89	12.04

* Vol. 6, Reports N. J. Geological Survey. Clay Industry, p. 256. 1904.

Even the common clay brick, therefore, is stronger and denser than the lime-sand brick.

Comparison with sandstone.—Lime-sand bricks are frequently compared, as to physical properties, with natural sandstones. One example of such a comparison is given on page 144 of this volume. In the table below the results of a large number of tests of natural sandstones are summarized.

TABLE 62.

SUMMARY OF TESTS OF NATURAL SANDSTONE.

	Compressive Strength, Pounds per Square Inch.			Absorption, Per Cent.		
	Max.	Min.	Average.	Max.	Min.	Average.
45 Wisconsin sandstones.....	13,669	1,658	6,429	15.22	2.00	7.46
9 Pennsylvania sandstones.....	29,252	11,448	17,225			
6 Massachusetts and Connecticut sandstones.....	16,894	4,945	12,192			
17 New York sandstones.....	19,968	4,025	12,893			

Comparing these results with those on lime-sand brick given in Table 60 above, it will be seen that the average natural sandstone is far superior in every way to the lime-sand brick.

Statistics of sand-lime brick industry.—In its recent revival the sand-lime brick industry in the United States dates back only to 1901, in which year a plant was established at Michigan City, Indiana. In the years immediately following a large number of plants were established in various parts of the country; and in 1907 as many as 94 plants were reported in operation, with a total product that year valued at over $1,225,000. In the years since then, however, there has been little or no increase in annual output; and a marked decrease in number of operating plants. The following table, quoted from the annual report of the United States Geological Survey, gives data covering this point.

OUTPUT OF SAND-LIME BRICK IN UNITED STATES, 1911–1920.

Year.	Operating Plants.	Output Brick, Thousands.	Year.	Operating Plants.	Output Brick, Thousands.
1911	66	142,963	1916	53	227,344
1912	71	178,541	1917	47	187,546
1913	68	189,659	1918	42	98,399
1914	62	172,629	1919	35	146,947
1915	56	179,643	1920	35	162,289

PART III. MAGNESIA AND OXYCHLORIDE CEMENTS.

CHAPTER XI.

SOURCES AND PREPARATION OF MAGNESIA.

MAGNESIA, or magnesium oxide (MgO), though possessing very marked cementing properties, is at present too expensive to be used as a cementing material for ordinary structural purposes. It merits discussion in this volume, however, because (*a*) it is the basis of an extensive magnesia brick industry; (*b*) under certain conditions it possesses hydraulic properties; and (*c*) the facts brought out in a description of the manufacture of magnesia and magnesia brick may serve to throw some light on the vexed question of the part played by magnesia when present in hydraulic cements.

Sources of magnesia.—Magnesia may be obtained on a commercial scale either by burning the mineral magnesite, a natural carbonate of magnesium, or by chemical methods practiced on other natural sources of magnesium salts such as highly magnesian limestones or even seawater. At present magnesite is by far the most important source of magnesia, but the chemical methods of extraction may be of service under certain commercial conditions. All the sources and methods will therefore be considered in the present chapter, magnesite being first discussed and then the chemical sources of supply. The chapter following will be devoted to consideration of the properties and uses of the magnesia, however obtained, and the manufacture and properties of magnesia bricks.

Magnesite as a Source of Magnesia.

Composition and character of magnesite.—Magnesite occurs commonly as a fine-grained, compact mineral, varying from white to yellowish in color according to its degree of purity. It is hard and brittle;

if cold hydrochloric acid be dropped upon it no action takes place, but hot acid causes brisk effervescence.

In composition it is a magnesium carbonate, corresponding to the formula $MgCO_3$. This is equivalent to magnesium carbonate ($MgCO_3$) = magnesium oxide or magnesia (MgO) + carbon dioxide (CO_2). Quantitatively, pure magnesite ($MgCO_3$) consists of 47.6 per cent magnesia (MgO), 52.4 per cent carbon dioxide (CO_2).

Occurrence and origin of magnesite.—Magnesite, when in bodies of workable size, occurs commonly in one of three associations, the methods of origin of the deposits being different in each case. The three types of deposits are:

(1) Magnesite occurs most commonly in the form of irregular veins or pockets in serpentine or other magnesian igneous rocks. In this case the magnesite has been formed as a decomposition product arising from the decay of the igneous rock.

(2) Magnesite occurs in the form of beds associated with deposits of rock salt, gypsum, etc. In this case the magnesite deposit has undoubtedly originated by direct deposition of magnesium carbonate from bodies of concentrated saline waters.

(3) Magnesite also occurs in the form of beds interstratified with shales, limestones, etc. Magnesite deposits of this type are commonly ascribed to the replacement of the lime (in a limestone) by magnesia carried in by percolating waters. This may be true in some cases, but such deposits may also have originated by direct deposition, as described under (2), above.

Of the magnesite deposits now worked, those of Greece, California, Lower California, Venezuela, Silesia and India are ascribed to the first mode of origin described above, being in all cases closely associated with igneous rocks. The undeveloped deposits described by Gale and by Shannon as occurring in Nevada and in Idaho are ascribed to the second or clearly sedimentary class. The deposits of Austria, Hungary, Czecho-Slovakia, Washington and Quebec are representative of the third group, being associated with limestones and metamorphic rocks.

World production of magnesite.—The magnesite industry of the world was completely dislocated by the World War, owing to two factors—the cutting off of normal sources of supply, and the direction of the products into certain special uses. As neither of these conditions is permanent, we have to examine a long series of years in order to get any fair idea as to the probable development of the industry in future. Working conditions will become slowly reestablished everywhere; freight rates will fall off very much below their war levels; and the uses

to which the product is put will be somewhat different, proportionately, in time of peace than they were during the war.

The magnesite output of the world is reported as follows in *Mineral Resources U. S. for 1920*, the quantities given being in metric tons.

TABLE 63.

MAGNESITE PRODUCTION OF WORLD, 1913–1920.

Country.	1913.	1914.	1915.	1916.	1917.	1918.	1919.	1920.
Australia	7,217	2,055	1,815	4,032	9,606	4,157	9,767	
Austria-Hungary*	422,439	279,651	78,314	81,771	106,783	†	†	
Canada	.....	.....	26,815	52,387	57,397	52,276	18,968	29,447
Greece	98,517	136,701	159,981	199,484	162,938	39,340	29,885	
India	14,457	1,707	7,569	17,922	18,493	5,947	17,401	
Italy	600	1,140	9,200	18,252	31,070	28,882	35,930	
Spain	958	583	1,400	2,500	800	1,700	120	
Union of South Africa	403	519	569	553	709	756	929	
United States	8,738	10,245	27,668	140,589	287,429	210,107	141,725	275,571
Venezuela‡	.....	.....	.....	6,360	1,700	.....	.....	2,300
	553,329	432,601	313,331	523,850	676,925	343,165	254,725	

* Exports computed on basis of 2.1 tons crude to 1 ton sintered.
† Figures not available.
‡ Figures not verified.

By far the bulk of the total output is applied to one of two broad uses—for refractory purposes, particularly in the steel and copper industries, and for structural purposes, as flooring, etc. During the war perhaps as much as three-quarters to four-fifths of the total supply went for refractory uses; in future the chief development is likely to be along the other line, so that we may see half the magnesite output applied, in the form of oxychloride cement mixtures, to purely structural uses.

American magnesite deposits.—The deposits now worked extensively are in the states of Washington and California, and in the province of Quebec. Less important tonnages are shipped from mines in Lower California and Venezuela. Deposits are known to exist in other regions, notably in British Columbia and Newfoundland.

California.—The California industry grew up rapidly during the war, from a few thousand tons annually to 211,663 tons in 1917. From then on it fell off in common with magnesite production everywhere, but in the case of California the decrease was accentuated by the opening of the large deposits in Washington. The total magnesite reserves in California are placed at some 1,000,000 tons of commercial ore.

The California deposits are scattered along the Coast Range from Mendocino County on the north to Riverside County on the south; and along the western slope of the Sierra Nevada from Placer County to Kern County. The largest deposits are in Red Mountain, south of Livermore, Santa Clara County; in Sampton Peak, San Benito County; and in the vicinity of Porterville, Tulare County.

Washington.—The magnesite deposits in Washington are in Stevens County, near Valley and Chewelah. These deposits were opened originally as marble and serpentine quarries. The discovery that they were not calcite marbles but in reality more or less pure magnesites was made by the present writer and published in 1912.* Some four years later, under stress of war conditions, the discovery was put to practical use, and a heavy production has resulted. This reached a maximum in 1920, when 221,985 short tons of magnesite were mined in Washington. Practically all of this output was calcined locally and shipped for refractory purposes. The reserve of ore suitable for refractory use is now estimated at around three to four million tons; perhaps an equal quantity of lower grade ore exists.

Quebec.—The magnesite deposits of Quebec are located in Argenteuil County, about midway between Ottawa and Montreal, to the north of the Ottawa River. The deposits are of coarsely crystalline magnesite, closely associated with beds of magnesian limestone, quartzites, schists, etc. Wilson estimates ore reserves at over one million tons. The deposits were developed during the war, and reached the maximum output of 58,090 tons in 1917.

The Quebec magnesite, as shown by the analyses in table 65, ranges low in iron and high in lime. This necessitates the addition of iron ore when the product is being sintered to give dead burned magnesia.

Foreign localities.—The principal European magnesite deposits are near Mittendorf, in Styria, and near Tolsvar, in the province of Minsan, Hungary. The Styrian magnesite averages about 88 per cent magnesium carbonate with about 8 per cent of silica, alumina, and iron oxide. The Hungarian product is a purer magnesite, carrying 92 to 95 per cent magnesium carbonate, with 3 or 4 per cent iron oxide.

In Germany the deposits now worked occur near Kosewitz and Frankenstein, in Silesia, and are principally worked in connection with the manufacture of carbonic acid. The product will carry about 92 to 94 per cent magnesium carbonate, the principal impurity being 4 to 5 per cent of silica.

The principal Grecian deposits are on the island of Eubœa, on the

*Eckel, E.C., Building Stones and Clays, New York, 1912, p. 84, etc.

east coast of Greece, and also near Corinth. The product is a very pure magnesite, averaging 95 per cent magnesium carbonate. It is low in clayey matter, the principal impurity being 3 to 5 per cent of lime carbonate. The Grecian deposits are worked in primitive fashion by pick and shovel. The mines, or quarries, are usually worked as open cuts. As the rock is broken in the mines it is brought to the surface, where the magnesite is sorted out. It is then loaded into small carts and drawn to a narrow-gauge gravity railway, when the magnesite is loaded into one-ton cars and sent forward to the shipping port, usually Kymassi or St. Theodore. The cost of producing the mineral is about $3.50 per ton, transportation charges to the seaport about $1.00, and freight to the United States about $2.50 per ton. (1903.)

TABLE 64.

ANALYSES OF MAGNESITE, CALIFORNIA, WASHINGTON, AND NEVADA.

	1.	2.	3.	4.	5.	6.
Silica	6.17	0.14	9.64	4.75	0.90	0.50
Alumina and iron oxide	0.80	0.48	2.46	0.76	0.49	0.30
Lime (CaO)	trace	0.59	4.25	trace	1.49	0.70
Magnesia (MgO)	43.80	47.07	37.19	44.20	44.39	46.90
Carbon dioxide	45.02	50.66	40.70	47.32	50.06	51.60

	7.	8.	9.	10.	11.
Silica	1.81	0.89	5.79	11.12	11.82
Alumina and iron oxide	0.08	0.58	1.28	0.98	0.94
Lime (CaO)	trace	trace	1.69	5.36	5.90
Magnesia MgO)	46.55	45.76	42.07	36.72	36.40
Carbon dioxide	51.25	49.24	47.23	44.15	43.45

1. Winchester, Riverside County, Cal.
2. Idria, San Benito County, Cal.
3, 4. Bissell, Kern County, Cal.
5. Porterville, Tulare County, Cal.
6. Livermore, Alameda County, Cal.
7, Chiles Valley, Napa County, Cal.
8, 9. Valley, Stevens County, Wash.
10, 11. Muddy River, Clark County, Nev.

Magnesite is found in considerable quantity in southern India, about 200 miles from Madras. Deposits recently exploited extend over 1500 acres. The railroad from Madras to Calicut runs through these deposits, near the center of the magnesite area. The material can be shipped, in any desired quantity, either from Madras on the east coast or from Beypore on the west coast. As described to the present writer by the owner, the magnesite occurs in beds or veins of varying thickness, from a few inches up to several feet, the magnesite beds being separated by bodies of disintegrated material. An analysis of this magnesite is given in column 1, Table 66. This was made on a 100-ton sample of crude rock. Another analysis of Indian magnesite,

quoted in column 2 of the same table, accompanied a series of specimens exhibited at the St. Louis Exposition in 1904.

TABLE 65.

ANALYSES OF MAGNESITE, QUEBEC, CANADA.

Insoluble mineral matter	2.20	3.08	2.00	2.00	0.74
Iron oxide	0.13	0.29	0.57	0.50	0.24
Alumina	0.03	0.35	1.47	0.80	0.36
Lime	8.80	10.06	5.80	6.95	10.05
Magnesia	39.12	37.76	41.34	40.76	38.52
Carbon dioxide	49.72	49.39	49.66	49.88	49.86

TABLE 66.

ANALYSES OF MAGNESITE, EUROPE AND ASIA.

	1.	2.	3.	4.	5.
Silica (SiO_2)	2.20	0.22	0.30	0.52	0.52
Alumina (Al_2O_3)	0.30	0.30	1.62	trace	0.08
Iron oxide (Fe_2O_3)					
Lime (CaO)	0.59	n. d.	n. d.	2.25	2.46
Magnesia (MgO)	46.59	47.35	46.00	45.28	44.96
Carbon dioxide (CO_2)	49.63	51.44	51.23	51.61	51.44
Water	0.83	0.27	n. d.	0.34	0.54

	6.	7.	8.	9.
Silica (SiO_2)	1.0	4.00	0.8	4.5–5.25
Alumina (Al_2O_3)	3.0–6.0	4.00	1.1	1.5
Iron oxide (Fe_2O_3)			3.2	
Lime (CaO)	0.28–1.12	n. d.	0.06	0.6–0.7
Magnesia (MgO)	42.84–45.70	41.89	45.12	46.0–48.0
Carbon dioxide (CO_2)	n. d.	n. d.	49.72	46.0–50.0

1. 200 miles from Madras, British India. Private communication.
2. India. Indian Exhibit, World's Fair, St. Louis, 1904.
3. Dept. of Ufa, Southern Urals, Russia. "Mineral Industry," vol. 10. p. 439.
4. Mondondi, Greece. U. S. Consular Reports, No. 168, 1900.
5. Eubœa, Greece. Proc. Inst. C. E., vol. 112, p. 381.
6. Styria. Proc. Inst. C. E., vol. 112, p. 381.
7. Styria. Eng. and Mining Journal, March 10, 1900.
8. Minsan, Hungary. Eng. and Mining Journal, March 10, 1900.
9. Frankenstein, Silesia. Eng. and Mining Journal, March 10, 1900.

Analyses of commercial magnesite.—As magnesite is simply magnesium carbonate, a theoretically pure magnesite would consist of 47.6 per cent magnesia (MgO) and 52.4 per cent carbon dioxide (CO_2). Deposits of magnesite, however, rarely yield any considerable amount of material of this degree of purity, and commercial magnesite may contain as high as 10 per cent or thereabouts of lime carbonate, silica, alumina, iron oxide, etc.

Effects of heating magnesite.—If magnesite ($MgCO_3$) be strongly heated, the effect (as with lime carbonate) is to drive off the carbon dioxide (CO_2), leaving magnesia (MgO) as a white solid. A curious and technologically important phenomenon connected with the temperature employed is to be noted. If the calcination be carried on quickly at a red heat, the magnesia resulting will have a specific gravity of 3.00 to 3.07; while if the calcination is long continued or carried on at a higher temperature the resulting magnesia will be much denser, possessing a specific gravity of 3.61 to 3.80.

The technologic importance of the two forms of magnesia lies in the fact that the lightly burned magnesia will slake with water and if then exposed to air will finally recarbonate and harden slowly, just as lime does. The denser, higher-burned magnesia, however, will not take up either water or carbon dioxide from the atmosphere. Another difference of commercial interest lies in the fact that the light form of magnesite possesses a certain amount of plasticity, so that it can be molded into shape under heavy pressure, while the dense form of magnesia is entirely devoid of plasticity.

Methods of burning magnesite.—For calcining magnesite at low temperature, so as to obtain lightly burned magnesia, kilns closely similar to ordinary lime-kilns are employed in California. The kilns in use at one California magnesia-plant are built in the form of a frustum of a cone, the broader part downwards. These kilns are about 19 feet in height, 3 feet in diameter at the top, and 7 feet in diameter at the base. Drawing-doors are placed at the base, while draft is obtained by suction, air being drawn through a flue near the top of the kiln. These kilns are charged with coke and magnesite mixed, in about the proportion of 300 lbs. magnesite to 20 lbs. of coke. The product is the light form of magnesite, and is probably not entirely decarbonated. This fuel consumption would amount to about 14 per cent on the weight of magnesia produced.

When the dead-burnt or heavy magnesia is required, the burning must take place at much higher temperatures. This kind of magnesia may be prepared in reverberatory furnaces, in cupolas lined with silicious material, or in highly heated gas-kilns.*

The practice in Greece is described † as follows:

"At the Greek magnesite mines, until recently roughly built kilns fired by wood were employed for calcining the ore, which required a large quantity of fuel. In recent years, however, modern shaft cal-

* Proc. Inst. Civil Engineers, vol. 112, p. 381. 1893.

† Engineering and Mining Journal, Feb. 28, 1903.

ciners have been built and a soft lignite coal is used. When calcined, magnesite falls into powder and is apt to choke the lower or cooler portion of the kiln, preventing the access of air and heated gases to the uper portion. The shaft furnaces are constructed to overcome this result. The quantity of fuel required is from 15 to 20 per cent of the weight of magnesite, equivalent to a fuel consumption of 30 to 40 per cent on the weight of magnesia produced. In some cases the calcining is done in a double-hearth reverberatory furnace, where the flame is brought into direct contact with the freshly charged magnesite on the upper hearth, the operation being completed on the lower hearth, which is the hotter of the two."

Composition of the product.—The analyses given in Table 67 will serve to show the composition of the burned product, which naturally varies according to that of the magnesite from which it is made.

TABLE 67.

ANALYSES OF CALCINED MAGNESITE (=MAGNESIA).

	1.	2.	3.	4.	5.	6.	7.
Silica (SiO_2)	0.98	0.16	0.17	0.50	.....	1.2	0.73– 7.98
Alumina (Al_2O_3)	0.10	0.10	2.38	.....	.....	13.0	0.56– 3.54
Iron oxide (Fe_2O_3)	5.70	7.40	5.02	6.50	6.90		
Lime (CaO)	1.88	2.66	1.50	1.70	.....	7.3	0.83–10.92
Magnesia (MgO)	91.10	89.36	90.42	90.95	91.50	77.6	82.46–95.36
Carbon dioxide (CO_2)	n. d.	n. d.	0.46	n. d.	n. d.		

1, 2. Burned Hungarian magnesite. Iron Age, Jan. 15, 1903, pp. 20, 21.
3, 4, 5. Burned Hungarian magnesite. Mineral Industry, vol. 10, p. 439.
6. Burned Styrian (Austrian) magnesite. Proc. Inst. C. E., vol. 112, p. 381.
7. Burned Grecian magnesite. Proc. Inst. C. E., vol. 112, p. 381.

Use of magnesite for preparation of carbonic acid, etc.—California practice in the manufacture of carbonic acid from magnesite is described as follows in a recent report:*

" In the manufacture of carbonic-acid gas, the gas is extracted from the magnesite by calcining and the remaining calcined material is sold to the manufacturers of wood-pulp paper. The best English coke is used for calcining the magnesite. From one short ton of magnesite, after removing the gas, they obtain about 1200 lbs. of residue, which is partly calcined magnesite still carrying some 20 per cent of gas. In the process about 500 lbs. of gas is obtained when finally compressed into liquid form. For every ton of magnesite about 500 lbs. of coke is burned, and this, containing about 97 per cent of carbon, also fur-

* Mineral Resources of the U. S. for 1903, p. 1133. 1904.

nishes considerable gas. The steel cylinders for holding the liquid gas are $\frac{3}{16}$ inch thick and 5 by 49 inches long, and hold about 25 lbs. The pressure on the cylinder at 60° F. is about 850 lbs., a three-stage compressor being used. In shipping the liquid gas through the central valleys and to Arizona the heat in the cars sometimes runs as high as 145°, the pressure being increased thereby. The cylinders containing the liquefied gas are shipped to soda-water manufacturers, ice-factories, refrigerating-plants, breweries, bar-rooms, etc. The cylinders with the liquid gas are shipped all over the Pacific coast from San Francisco, even the British war vessels stationed at British Columbia using the gas for their refrigerating-plants. The San Francisco carbonic-acid-gas makers use about 1000 tons of crude magnesite annually.

As stated, the wood-pulp paper-mills of California and Oregon use the calcined magnesite. They transform it into a sulphite of magnesia and use it as a digester for the wood pulp. To make this sulphite they put the material into a tank and pass sulphurous fumes through it. After being used as a digester they add a little lime and make the ' pearl hardening ' of commerce to be used as a ' filler ' for the paper."

Magnesian Limestones as Sources of Magnesia.

Highly magnesian limestones, approaching dolomite in composition, may be regarded as possible sources of magnesia. The general characters of such limestones are discussed in some detail in earlier chapters of this volume, and reference should be made to pp. 93–94 for data on these points.

Occurrence of magnesian limestones in the U. S.—Magnesian limestones are so widely distributed throughout the United States that no satisfactory summary of their distribution can be given here. On pp. 94–95 is given a list of reports on the limestones of the various states and territories. Reference to these reports will furnish data on the local distribution and composition of magnesian limestones, as well as of other types.

Analyses of magnesian limestones.—In the following table analyses of a number of highly magnesian limestones from various localities in the United States are presented. It will be seen that these range from 15 to over 22 per cent in magnesia (MgO), which is about equivalent to a range of from 32 to 45 per cent magnesium carbonate ($MgCO_3$).

Extraction of magnesia from magnesian limestone.—Two principal processes have been suggested for extracting magnesia from magnesian limestone.

TABLE 68.

ANALYSES OF HIGHLY MAGNESIAN LIMESTONES, U. S.

	1.	2.	3.	4.	5.
Silica (SiO_2)	3.24	7.75	.....	0.48	0.08
Alumina (Al_2O_3)	0.17	1.48	....	0.20	
Iron oxide (Fe_2O_3)	0.23		0.02		0.25
Lime (CaO)	29.58	31.00	31.01	31.31	30.46
Magnesia (MgO)	20.84	16.46	21.79	21.03	21.48
Carbon dioxide (CO_2)	45.54	42.47	47.35	46.98	47.58

	6.	7.	8.	9.	10.
Silica (SiO_2)	0.73	0.44	0.87	0.20	0.70
Alumina (Al_2O_3)	0.35	1.22	0.57	0.23	0.95
Iron oxide (Fe_2O_3)		trace	0.25		0.80
Lime (CaO)	32.73	30.73	31.40	30.04	30.50
Magnesia (MgO)	19.37	20.87	19.95	22.28	20.05
Carbon dioxide (CO_2)	46.58	45.85	n. d.	47.14	45.24

1. Morrisville, Calhoun County, Ala. W. F. Hillebrand, analyst. Bulletin 60, U. S. Geol. Survey, p. 159.
2. S. 16, T. 7, R. 7, E. Talladega County, Ala. J. B. Britton, analyst. Rep. Ala. Geol. Survey for 1875, pp. 149, 150.
3. Inyo Marble Co., Inyo, Calif. 20th Ann. Rep. U. S Geol. Survey, pt. 6, p. 359.
4. East Canaan, Conn. 20th Ann. Rep. U. S. Geol. Survey, pt. 6, p. 370.
5. Canaan, Conn. J. S. Adams, analyst. 20th Ann. Rep. U. S. Geol. Survey, pt. 6, p. 370.
6. Jasper, Ga. W. H. Emerson, analyst. Bulletin No. 1, Ga. Geol. Survey, p. 87.
7. Cockeysville, Md. J. E. Whitfield, analyst. Bulletin 60, U. S. Geol. Survey, p. 159.
8. Ossining, N. Y. H. Ries, analyst. Bulletin 44, N. Y. State Museum, p. 829.
9. Tuckahoe, N. Y. Ledoux, analyst. 20th Ann. Rep. U. S. Geol. Survey, pt. 6, p. 427.
10. Gates, Monroe County, N. Y. D. H. Newland, analyst. Bulletin 44, N. Y. State Museum, p. 796.

Scheibler process.—The mixture of lime and magnesia left by burning magnesian limestone is made into a thick milk by adding sufficient water. Into this solution is poured water containing 10 to 15 per cent, by volume, of molasses, and the mixture is mechanically stirred. In a few moments saccharate of lime is formed, which remains in solution while the magnesia is precipitated. On putting through a filter-press the magnesia remains behind, while the saccharate of lime passes through. The composition of the magnesia so obtained at a German plant was:

Silica (SiO_2), Alumina (Al_2O_3), Iron oxide (Fe_2O_3)	1.47 per cent
Lime (CaO)	2.18 " "
Magnesia (MgO)	95.99 " "

The saccharate of lime which passed through the filters is now treated for recovery of its constituents. Carbon dioxide precipitates the lime as carbonate, after which it is filtered and the lime carbonate precipitate washed. The filtrate contains the molasses, which can be used

over again. In the course of the process a loss of 5 to 10 per cent of molasses occurs.

Closson process.—This process is based on the use of magnesium chloride, and is therefore of value at points such as Stassfurt, where that material is obtainable as a cheap by-product.

Twenty thousand pounds of magnesium chloride is mixed with the lime-magnesia resulting from the calcination of 3000 lbs. of magnesian limestone. Water is added to give a thick solution, and mechanical agitation is employed. The result is the formation of lime chloride and magnesia hydrate. On passing through a filter-press the magnesia hydrate is caught on the filter, while the lime chloride passes through in solution. The hydrate is washed and then burned, giving one ton of magnesia. The magnesia obtained at Horde by this process gave the following composition:

Silica (SiO_2), Alumina (Al_2O_3), Iron oxide (Fe_2O_3)	1.05 per cent
Lime (CaO)	1.94 " "
Magnesia (MgO)	96.90 " "

The lime-chloride solution is then treated for recovery. The material is carried to receptacles like those in which blast-furnace gases are washed, except that revolving wheels stir the chloride, making a thorough mixture of the gases and the liquid. Two of these receptacles are placed together back to back. A valve which can be reversed sends the gases to either side and thus keeps up a continuous working. Into these receptacles, together with the lime chloride, is put a quantity of the lime-magnesia resulting from the calcination of magnesian limestone. The blast-furnace gases passing through precipitate the lime as carbonate, losing their carbon dioxide in the process, and are thus rendered more combustible. They deposit, besides, a considerable quantity of the solid materials mechanically carried by them and are thus cleaned. Magnesium chloride is reformed, remains in solution, and is drawn off and filtered. The entire process shows a loss of 5 to 6 per cent of magnesium chloride.

Sea-water and Brines as Sources of Magnesia.

Sea-water contains small percentages of different magnesian salts. In the manufacture of table salt from sea-water or salt brines, these magnesian compounds are incidentally concentrated so as to be put in more available form.

Extraction of magnesia from sea-water.*—"Magnesia is made out of sea-water, which contains about 4 lbs. magnesium chloride per cubic yard of water, on a large scale at Aigues Morts, on the Mediterranean coast of France.

"The sea-water is pumped into a tank made of masonry, and at the same time milk of lime is pumped in, in the proportion of 1.5 per cent of lime for every 1 per cent of magnesia. From this first tank the liquid flows into two other masonry tanks, when thorough mixing is effected mechanically. It is then filtered into shallow excavations about 1000 feet long and 16 feet wide, in the bottom of which is a bed of clean beach-sand. When enough magnesia has been collected the liquid supply is cut off and the precipitate is allowed to dry. If in summer, it is dried in the sun, taking twenty to thirty days, but in winter artificial drying is necessary." The dried magnesia is then calcined and treated as explained in discussing the burning of magnesite (p. 155), and the manufacture of magnesia bricks (pp. 161–163).

References on magnesite, sources of magnesia, etc.

Gale, H. S. Magnesite deposits in California, Min. Res. U. S. for 1911, vol. 2.

Gale, H. S. Magnesite near Muddy River, Nevada. Min. Res. U. S. for 1920, vol. 2.

Hess, F. L. The magnesite deposits of California. Bulletin 355, U. S. Geol. Survey, 1908.

Hoffmann, G. C. Magnesite deposits in Quebec, Canada. Ann. Rep. Canadian Geological Survey, vol. 13, Report R, pp. 14–19. 1903.

Morganroth, L. C. Occurrence, preparation and use of magnesite. Trans. Am. Inst. Min. Engrs., Oct., 1914.

Scherer, R. Der Magnesit. 256 pp., Vienna, 1908.

Shannon, E. V. Magnesite in Idaho. Min. Res. U. S. for 1920, vol. 2.

Vlasto, S. J. The magnesite industry [in Europe]. Engineering and Mining Journal, March 10, 1900.

Weiss, N. Magnesite in Hungary. Iron Age, pp. 20–21. Jan. 15, 1903.

Wilson, M. E. Magnesite deposits of Argenteuil County, Quebec. Memoir 98, Canadian Geol. Survey.

* Lock, C. G. W. Economic Mining, p. 331.

CHAPTER XII.

MAGNESIA BRICKS AND OXYCHLORIDE CEMENTS.

After magnesia (MgO) has been obtained by any of the methods described in the preceding chapter, it is put to use in two quite different ways. As the products differ greatly in both composition and use they will here be discussed separately under the headings of " Magnesia Bricks " and " Oxychloride Cements."

Magnesia Bricks.

Magnesia bricks, which are commonly but very erroneously called *magnesite* bricks in the trade, are largely used as furnace linings, etc., and have also been used to a small extent as linings for Portland-cement kilns.

Manufacture of magnesia bricks.—In discussing the methods and effects of calcining magnesite it was stated that two different forms of magnesia could be obtained, according to the temperature at which the calcination is carried on. If the magnesite be burned at a light-red heat, the resulting magnesia will have a low specific gravity (3.00 to 3.07), will possess sufficient plasticity to be capable of being molded into shapes, and will gradually absorb water and carbon dioxide from the atmosphere, just as quicklime would do. The result of this absorption is that this form of magnesia will finally become partly recarbonated.

If the calcination takes place at a higher temperature, however, the resulting magnesia will be heavy, with a specific gravity of 3.61 to 3.80; it will be absolutely devoid of plasticity; and it will not recarbonate on exposure to the atmosphere.

These differences in the physical and chemical properties of the two forms of magnesia are taken advantage of in the manufacture of magnesia bricks. Each contributes certain good qualities to the brick.

Magnesia bricks are made of a mixture of the two forms of magnesia, in the proportions of four to six parts heavy magnesia to one part light magnesia. The dense, chemically stable " heavy magnesia " is thus the *base* of the brick; the light magnesia is added to give plasticity to the mixture, enabling it to be molded, and also to harden on exposure to the atmosphere.

From 10 to 15 per cent of water is added to this mixture, and the resulting stiff paste is pressed into form in iron molds. The brick will gradually harden on simple exposure to the air, after which it is usually made still more resistant by reburning at a low red heat. Bricks or other objects made in this manner may, if not sufficiently solid for the use for which they are intended, be hardened by dipping into a cold dilute solution of boracic acid in water. After this they should be dried and reburned.

Composition of magnesia bricks.

TABLE 69.

ANALYSES OF MAGNESIA BRICKS.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	0.35	3.45	3.10	3.4	3.2	2.16
Alumina (Al_2O_3)	.....	1.30	6.64	0.98	0.69	0.72
Iron oxide (Fe_2O_3)	6.05	7.60		5.1	0.3	
Lime (CaO)	2.10	3.90	3.76	2.8	1.9	4.20
Magnesia (MgO)	91.52	83.00	86.50	87.8	93.88	93.93
Carbon dioxide (CO_2)	.....	.....	.....	0.04	0.14	

1. Brick made from Hungarian magnesite. Mineral Industry, vol. 10, p. 439.
2. " " " Styrian " " " " vol. 10, p. 439.
3. " " " " " Trans. Am. Inst. Min. Engrs., vol. 26, p. 268.
4. " " " " " Mineral Industry, vol. 10, p. 439.
5. " " " Grecian " " " vol. 10, p. 439.
6. " " " " " Trans. Am. Inst. Min. Engrs., vol. 26, p. 268.

Physical properties of magnesia bricks.—The brick * whose analysis is given in column 3 of Table 69 was made in Pittsburgh from Styrian magnesite. Its specific gravity was 3.44, equivalent to a weight of 160.9 lbs. per cubic foot. The brick whose analysis appears in column 6 of the same table was made from Grecian magnesite. Its specific gravity was 3.54, corresponding to a weight of 170.2 lbs. per cubic foot.

Le Chatelier tested two kinds of magnesite bricks (Austrian and Grecian) for expansion with increase of temperature, obtaining the results quoted in Table 70. The expansion given are in millimeters for a bar 100 mm. in length, and are therefore equivalent to percentages.

TABLE 70.

EXPANSION OF MAGNESITE BRICKS ON HEATING. (LE CHATELIER.)

	200° C.	400° C.	600° C.	800° C.
	mm.	mm.	mm.	mm.
Austrian magnesite brick	0.21	0.55	0.85	1.10
Grecian magnesite brick	0.25	0.52	0.79	1.02

* Trans. Am. Inst. Min. Engrs., vol. 26, p. 268.

References on magnesite bricks.—The following papers contain data regarding the manufacture and properties of magnesia bricks.

Bischof, C. On magnesia bricks. Proc. Inst. Civil Engineers, vol. 112, pp. 381–383. 1893.

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Percy, J. Magnesia crucibles and bricks. Metallurgy, vol. 1, pp. 134–137. 1875.

Vlasto, S. J. The magnesite industry. Engineering and Mining Journal, March 10, 1900.

Weiss, N. Magnesite in Hungary. Iron Age, Jan. 15, 1903, pp. 20–21.

Anon. Magnesite [and magnesia brick]. Mineral Industry, vol. 10, pp. 438–439. 1902.

Oxychloride Cements.

In 1853 the chemist Sorel discovered that zinc chloride, when mixed with zinc oxide, united with it to form a very hard cement. Later it was discovered that the same held true of a mixture of magnesium chloride and magnesia. The product in both cases is the same—an oxychloride of zinc or magnesium respectively. Chlorides and oxides of several other elements possess this same property, but it has been utilized commercially only in the cases of the zinc and magnesium compounds. Of these, zinc oxychloride is extensively used as a stopping by dentists. Magnesium oxychloride, called commonly Sorel cement or magnesia cement, has more important technical uses.

Sorel's magnesia cement is made by mixing calcined magnesia with a solution of magnesium chloride of 25° or 30° Baumé. If the magnesia has been prepared from magnesite, it usually contains a little residual carbon dioxide (CO_2), and though setting very rapidly and giving a very strong cement, cracks are apt to develop during setting. When made from magnesium chloride (see p. 159) the magnesia is free from carbon dioxide, and though it sets and hardens less rapidly, no cracks appear.

The commercial magnesium chloride used in the preparation of Sorel stone, etc., usually contains sulphuric acid. As this acid and its compounds spoil the appearance and the durability of the stone produced, it is eliminated from the magnesium chloride by treatment

with barium hydrate or barium carbonate. In practice,* the magnesium chloride is dissolved in water to form a solution of 20° to 25° Baumé, and the barium hydrate or carbonate is added by degrees and carefully stirred until the precipitate of barium sulphate ceases to increase. The amount of reagent required is usually between 6 and 10 per cent of the weight of the magnesium chloride treated.

Magnesia cement is used very extensively † as a binder, in connection with briquetting, in the manufacture of artificial building-stones, tiles, grindstones, and emery- and polishing-wheels. Its binding quality is very considerable, and it is very plastic and cheap. A good mixture for this use consists of 25 parts of magnesium chloride (45 per cent solution), 25 parts magnesia (93 per cent MgO), and 50 parts water. About 5 lbs. of this mixture will serve to cement 95 parts of stone, emery, etc. The resulting blocks are very solid and harden thoroughly within a few hours.

Gillmore, in 1871, prepared a report on certain American patented products based upon Sorel cements. As this report is still the only complete discussion of the subject it is reprinted below, almost verbatim.

"The several steps in the process, beginning with the raw magnesite, are briefly as follows, viz.:

"*First.* The magnesite is burnt in ordinary lime-kilns, at a dark cherry-red heat, for about twenty-four hours. The result is protoxide of magnesium, which is next ground to fine powder between horizontal millstones, furnishing what the Union Stone Company style 'Union cement.'

"Magnesite has been procured from various localities. That from Greece, California, Maryland, and Pennsylvania contains about 95 per cent of carbonate of magnesia, the residue being mostly insoluble silicious matter. The burnt product is perfectly white. A magnesite is procured in Canada which contains from 60 to 85 per cent of carbonate of magnesia. A variable percentage of iron in the residue gives the cement derived from this stone a reddish tint.

"*Second.* For making stone, the burnt and ground magnesite (oxide of magnesium) is mixed dry in the proper proportion with the material to be united; that is, with powdered marble, quartz, emery, silicious sand, soapstone, or with whatever substance forms the basis of the stone to be imitated or reproduced.

"The usual proportions are: for emery-wheels, 10 to 15 per cent of

* Journ. Soc. Chem. Industry, vol. 21, p. 257. 1902.

† Schorr, R. The briquetting of minerals. Eng. and Mining Journal, vol. 74, p. 673. 1902.

oxide of magnesium by weight; for building-blocks, such as sills, lintels, steps, etc., 6 to 10 per cent, and for common work for thick walls, less than 5 per cent.

"The dry ingredients are mixed together by hand or in a mill. A hollow cylinder revolving slowly about its axis would answer the purpose.

"*Third.* After this mixing they are moistened with chloride of magnesium, for which bittern water—the usual refuse of seaside salt-works—is a cheap and suitable substitute. The moistened material is then passed through a mill, which subjects it to a kind of trituration, by which each grain of sand or other solid material becomes entirely coated over with a thin film of the cement, formed by a combination of the chloride with the oxide of magnesium. The bittern water is required to be of the density of from 15° to 30° Baumé. The mass on emerging from the mill should be about as moist as molder's clay. The mixing-machine used by the Union Stone Company is an improved pug-mill invented by Mr. Josiah S. Elliott. It is represented as an excellent mill, doing its work thoroughly.

"*Fourth.* The mixture is formed into blocks by ramming or tamping it in strong molds of the required form, made of iron, wood, or plaster, precisely as described in paragraph 24, Report on Béton Aggloméré. The block may be taken out of the mold at once and nothing further need be done to it. The setting is progressive and simultaneous throughout the mass, as with other hydraulic cements, and requires from one hour to one day, depending somewhat on the chemical properties of the solid ingredients used, the carbonates as a rule requiring a longer time than the silicates.

"Building-blocks will bear handling, and may be used when three or four days old, although they do not attain their maximum strength and hardness for several months. Emery-wheels are not allowed to be used in less than four weeks.

"This stone so closely resembles the natural stone, whether marble, soapstone, sandstone, etc., from which the solid ingredients are obtained by crushing and grinding, that it is difficult, without the application of chemical tests, to detect any difference in either texture, color, or general lithological appearance.

"*Strength.*—In strength and hardness this stone greatly surpasses all other known artificial stones, and is equaled by few, if any, of the natural stones that are adapted to building purposes. The artificial marble takes a high degree of polish, being in this espect fully equal to the best Italian varieties.

"Some trials of 2-inch cubes at the Boston Navy-yard gave the following results, reduced to the crushing pressure upon one square inch:

No. 1, crushing strength per square inch..... 7,187½ lbs.
No. 2, " " " " " ..... 11,562½ "
No. 3, " " " " " ..... 21,562½ "
No. 4, " " " " " ..... 7,343½ "

"In none of these samples did the proportion of the oxide of magnesium exceed 15 per cent by weight of the inert material cemented together. This statement is derived from the treasurer of the company.

"The principal business of the Union Stone Company up to the present time has been the manufacture of emery-wheels. The great tensile strength of the material may be inferred from the fact that in the proof trials the wheels are made to revolve with a velocity of from 2 to 3 miles per minute at the circumference. They do not usually begin to break until a velocity of from 4 to 5 miles per minute is attained.

"From a number of specimens of this stone furnished the writer by the treasurer of the company, who also gave their age and composition as reported below, comprising coarse and fine sandstone of various shades of color, hones, white and variegated marble, emery-wheels, billiard-balls, concrete building-blocks, etc., some small blocks were prepared and subjected to crushing with the results given in Table 71.

TABLE 71.

COMPRESSIVE STRENGTH OF SOREL STONE.

Character of the Inert Materials.	Proportion by Weight of Oxide of Magnesium.	Age of Blocks.	Size of Blocks.	Total Crushing Strength.	Crushing Strength per Square Inch.
	Per Cent.			Lbs.	Lbs.
1. Coral sand.....	12	1 year	2" ×2¼"×1¼"	26,500	6,235
2. Pulverized quartz..	12 to 15	1 "	1¾"×2" ×1¾"	20,000	7,272
3. Washed flour of emery (a piece of hone).....	Not known	2 years	1¾"×2" ×1¾"	54,000	19,636
4. Fine marble.....	15	3 "	1¼"×1¼"×1¼"	26,000	11,555
5. Mill-sweepings.....	12 to 13	9 months	1¾"×2" ×1¾"	23,000	6,133
6. Marble and sand...	12	2 years	1¾"×2" ×1½"	16,000	4,923
7. Marble with colored veneer.....	Not known	Not known	1¼"×1¼"×1"	12,000	7,680

"*Durability.*—The proofs of the durability of the Union stone rests upon other evidence than that furnished by severe and prolonged climatic exposure. In Boston, however, building-blocks have resisted two

winters, and at the present time appear to be, and doubtless are, harder and stronger than before they were touched with frost.

"Dr. C. T. Jackson, State Assayer of Massachusetts, reports upon it as follows:

"'I find that the frost test (saturated solution of sulphate of soda) has not the power of disintegrating it in the least. The trial was made by daily immersions of the stone in the sulphate-of-soda solution for a week and allowing the solution to penetrate the stone as much as possible and then to crystallize. From this test it is evident that your stone will withstand the action of frost more perfectly than any sandstone or ordinary building stone now in use. I see no reason why it will not stand as well as granite.'

"A *perfect* resistance to the freezing and thawing of one winter may safely be accepted as conclusive evidence of the durability in the open air of an artificial stone of which the matrix is any kind of hydraulic cement. At no subsequent period will it be as likely to fail, from freezing and thawing, as during the first winter. A stone suitable for all kinds of building purposes on land might, however, fail under the solvent action of sea-water. On this head it can be said that magnesian compounds are understood to resist the immersion in the sea better than the compounds of alumina or lime.

"For these reasons this new stone has, with some exceptions, been limited in its application to articles of small bulk and great comparative value, for which other approved and less expensive artificial stone is either not suitable or of less practical value. Although for architectural ornaments of elaborate design it is perhaps less costly, even now, than granite or marble, it cannot hope to compete successfully for general adoption and use by engineers and architects with the béton aggloméré and the softer kinds of natural stone until the market price of the oxide of magnesium is greatly reduced. For the peculiar purposes to which it is adapted, it supplies what has heretofore been felt as a great want, and in this field, which is neither narrow nor unvaried, it has no prominent rival.

"The following formula has been found suitable for window-caps, sills, steps, etc. The quantities specified will make 1 cubic foot of stone.

100 pounds	of beach sand, cost $1.00 per ton at the works	$0.05
10 "	of comminuted marble, cost $5.00 per ton at the works	0.02½
10 "	of Union cement (oxide of magnesium)	0.50
10 "	of chloride of magnesium in solution, 20° Baumé	0.02
130 pounds	yielding 1 cubic foot of molded stone	$0.59½

"The labor, depending somewhat on the design as regards the degree and character of its ornamentation, will vary per cubic foot from 20 to 25 cents, making total cost of 1 cubic foot of finished building-block 79½ to 84½ cents. This price may be reduced 10 to 15 cents per cubic foot by incorporating large pebbles and small cobble-stones during the process of molding.

"For foundations and other plain, massive walls, the proportion of cement may be very considerably reduced and the quantity of cobble-stones increased."

Recent practice.—*Flooring cement.* The utilization of oxychloride cements for both flooring and stucco has extended so remarkably since the first edition of this book was prepared that it seems advisable to include several sets of formulae and instructions recently published on these points.

(1) Foreign practice in the home of the European magnesite industry is probably typified by the formulae given by Scherer in his book on magnesite. These formulae, for flooring cement, are as follows:*

MIXTURES FOR THE UNDERLYING OR COARSER LAYER.

[Parts by weight.]

1. 15 parts magnesia.
   10 parts magnesium chloride solution, 20° Baumé.
   10 parts moist sawdust.
   (Sets in 36 hours.)
2. 10 parts magnesia.
   10 parts magnesium chloride solution, 28° Baumé.
   5 parts sawdust.
   (Sets in 16 hours.)
3. 20 parts magnesia.
   15 parts magnesium chloride solution, 20° Baumé.
   4 parts ground cork.
   (Sets in 24 hours.)
4. 5 parts magnesia.
   3 parts magnesium chloride solution, 20° Baumé.
   5 parts ashes.
   (Sets in 24 hours.)

* Min. Res. U. S. for 1913, vol. 2, p. 453.

MIXTURES FOR OVERLYING OR SURFACE LAYERS.

[Parts by weight.]

1. 40 parts magnesia.
   33 parts magnesium chloride solution, 19° Baumé.
   10 parts asbestos powder.
   5 parts wood flour.
   1 part red ocher.
   (Sets in 24 hours.)
2. 25 parts magnesia.
   25 parts magnesium chloride, 21° Baumé.
   4½ parts wood flour, impregnated with 4¼ parts Terpentinharzlösung.
   15 parts yellow ocher.
   (Sets in 30 hours.)

The magnesia referred to by Scherer is of course the light-burned or caustic magnesia, not the dead-burned type. This remark holds true equally for all the following formulae for either flooring cement or stucco.

(2) The following specifications for magnesite cement are furnished by P. H. Bates, Bureau of Standards, Department of Commerce:

TABLE 72.

MAGNESITE FLOORING COMPOSITION.

	Per Cent by Weight.	
	Top Coat.	Under Coat.
Magnesium oxide	45	40
Wood flour	15	25
Asbestos	5	0
Color	10	10
Kaolin, talc, or kieselguhr	10	10
Silica	15	15

Of this mixture 90 per cent should pass a 100-mesh sieve, and 85 per cent of magnesium oxide and 90 per cent of silica should pass a 200-mesh sieve. After thoroughly mixing this dry material it should be wet with a 22° Baumé solution of magnesium chloride.

(3) Some years ago *Concrete* published * a formula, with instructions,

* Concrete, Jan. 1916, page 35.

covering the use of magnesia flooring cement as practiced by the Aberthaw Construction Co., of Boston. These data are as follows:

The following formula has been used with very good success:

10 pounds calcined powdered magnesite.
5 quarts to 7 quarts fine sand.
2 quarts to 3 pounds white talc.
6 quarts to 7 quarts " combined liquid."

The so-called " combined liquid " mentioned in this formula consists of magnesium chloride dissolved in clear water to a consistency of 22° to 24° Baumé in summer, and from 24° to 26° Baumé in winter and magnesium sulphate solution of 15°. To the magnesium chloride a 10% of magnesium sulphate solution is added to produce the " combined liquid." This liquid is boiled and skimmed before using. The dry materials are mixed thoroughly and the " combined liquid " solution added and slowly and carefully mixed so that the fiber and other materials will not become separated.

If a colored floor is desired, approximately 10% coloring mineral is added for red, brown or buff, and from 1% to 4% black for gray or black work. The colors are thoroughly mixed with the dry materials before adding the " combined liquid."

In laying a composition floor, so-called, on a concrete base the base should first be painted with a mixture of the combined liquid and magnesite after ascertaining that the base is thoroughly dry and clean. Over this the mixture is spread, making a floor from $\frac{3}{8}$ inch to $\frac{1}{2}$ inch thick. This gives a splendid wearing surface.

The mixture, in a pasty condition, is gradually worked out upon the floor to a proper thickness for using a straight-edge. The amount specified in the formula will cover 10 square feet of floor space $\frac{3}{4}$ inch thick. When the mixture has been properly spread and leveled, it is treated like a regular cement finish or top dressing, that is, when sufficiently set, it is worked with a trowel to a smooth surface.

In laying border floors, white pine strips are used to lay out the border. Inside this form the center panel is cast in any desired color. When this center panel has set sufficiently the pine strips are removed and the border cast in another color.

Recent practice: stucco.—The following data * cover recent developments along the line of using magnesia cements as stucco or wall coatings:

* Min. Res. U. S. for 1920, vol. 2.

(4) Specifications for magnesia stuccos, furnished by P. H. Bates, Bureau of Standards, Washington.

MAGNESITE STUCCO COMPOSITION.

	Per Cent by Weight.
Magnesium oxide	10–15
Silica, fine ground	20–25
Sand	70–60

This material is mixed dry and then wet with magnesium chloride of about 22° Baumé.

(5) The following specifications for magnesite stucco were proposed at a conference of the War Industries Board, October 17, 1918:

TABLE 73.

MAGNESITE STUCCO COMPOSITION.

Base Coat.	Pounds.	Finish Coat.	Pounds.
Magnesium oxide	335	Magnesium oxide	335
Asbestos fiber	40	Asbestos fiber	40
Granite-marble flour	150	Ground silica	100
Sand	1475	Sand—Ottawa	1525
	2000		2000
Magnesium chloride	320	Magnesium chloride	320

References on oxychloride cements, Sorel stone, etc.

Ebel [Magnesia cement concrete for use in mines]. Zeits. angew. Chemie, vol. 15, p. 44. Abstract in Journ. Soc. Chem. Industry, vol. 21, p. 175. 1902.

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Hooker, H. M. Composition Flooring. Proc. Eng. Soc. Western Pennsylvania, vol. 29, pp. 305–338, 418–444. 1913.

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PART IV. HYDRAULIC LIMES, SELENITIC LIME, AND GRAPPIER CEMENTS.

CHAPTER XIII.

THE THEORY OF HYDRAULIC LIMES.

BEFORE taking up the manufacture and properties of the various closely allied products—hydraulic limes, selenitic limes, and grappier cements—which are to be discussed in this part of the volume, it seems desirable to devote some space to a consideration of the general principles on which the manufacture and use of these products are based.

The materials heretofore discussed in this volume—the plasters, common lime, magnesia, etc.—have been simple in both composition and action. With the hydraulic limes, however, we take up the first member of a great class of very complex products. All these products possess hydraulic properties. In composition, they further agree in that they all consist essentially of silica, alumina, and lime, with or without magnesia and iron oxide. This group of complex cementing materials includes the hydraulic limes, the natural cements, the Portland cements, and the puzzolan cements. These four classes are quite distinct commercially, but it is at times difficult to draw the dividing line between the classes in words. Before defining the class of "hydraulic limes" it will therefore be well to explain the principal criterion which will be employed in drawing up that definition. This criterion is the "Cementation Index," a more satisfactory form of the older "hydraulic index."

The "Hydraulic Index."—In discussing the classification of cementing materials, in the introduction to this volume, the statement is made that the power of setting under water, possessed by the hydraulic limes and cements, is due to the formation of compounds of silica, alumina, and lime during the manufacture of the cementing materials in question. This being the case, it is a fair assumption * that the

* Strictly speaking, this statement is based on more than a mere assumption; but as a matter of convenience discussion of the reasons for it will be deferred to later chapters.

degree of hydraulic activity and the strength of any given cementing material will be related, in some way, to the proportions in which it contains these ingredients (silica, alumina, lime, etc.), and to the manner in which they are combined.

It is obvious that it would be of great value to both manufacturer and engineer if we could devise some method for *quantitatively* expressing this relation between the composition and the hydraulic value of any given sample of cementing material. Several methods of doing this have been suggested and used by various authorities.

Of these methods of expression, the one that has come into most general use is based upon the calculation of the "hydraulic index." The "hydraulic index," as usually defined, is the ratio between the percentage of silica plus alumina to the percentage of lime (CaO). A hydraulic lime, for example, such as that from Metz (Analysis No. 2, Table 76), containing 18.47 per cent silica, 5.73 per cent alumina, and 68.19 per cent lime would therefore have for its hydraulic index

$$\frac{18.47+5.73}{68.19}=\frac{24.20}{68.19}=0.355\ (\textit{Hydraulic Index}).$$

The "hydraulic index," calculated in this manner, is then used as a basis for classifying cementing materials according to their hydraulic activity. The following grouping, which is substantially that given by Spalding,† is an example of this:

Hydraulic Index.	Product.
Less than 0.10.....	Common lime, quicklime
0.10 to 0.20.....	Feebly hydraulic limes
0.20 " 0.40.....	Eminently hydraulic limes
0.40 " 0.60.....	Portland cement (if burned at high temperature)
0.60 " 1.50.....	Natural cements
1.50 " 3.00.....	Weak natural cements
3.00.....	Puzzolanas, etc.

The "hydraulic index" calculated and used in this fashion is certainly better than nothing, but it possesses defects which render it valueless in dealing with certain classes of cements. These defects arise chiefly from the facts that in calculating the "hydraulic index" (1) no allowance is made for the action of either magnesia or iron oxide, and (2) the assumption is made that silica and alumina are quantitatively interchangeable, i.e., that 10 per cent of silica will have exactly the same effect as 10 per cent of alumina.

These defects have led the writer to abandon the use of the "hydraulic

† Spalding, F. P. "Hydraulic Cement," pp. 8, 31, 38.

index" and to substitute therefor the index described in the next section as the "Cementation Index."

The Cementation Index.—As explained and defined below, the Cementation Index is a natural outgrowth from the formula proposed by Newberry for proportioning Portland-cement mixtures. The index now proposed differs from that formula in assigning values for the magnesia and iron oxide contained in the cement or lime, a change which is necessary in order to adapt it for use with the magnesian natural cements and the puzzolan cements. The proposed index is:

$$\text{Cementation Index} = \frac{(2.8 \times \text{percentage silica}) + (1.1 \times \text{percentage alumina}) + (.7 \times \text{percentage iron oxide})}{(\text{Percentage lime}) + (1.4 \times \text{percentage magnesia})}.$$

EXAMPLE.—As an example of the details of calculating the Cementation Index, the hydraulic lime of Metz, whose analysis is given as No. 2 of Table 79, will be used. The essential ingredients of this lime, as given in the quoted analysis, are:

Silica (SiO_2)	18.47
Alumina (Al_2O_3)	5.73
Iron oxide (Fe_2O_3)	3.29
Lime (CaO)	68.19
Magnesia (MgO)	2.66

Substituting these values in the formula

$$\text{Cementation Index} = \frac{2.8 \text{ percentage silica} + 1.1 \text{ percentage alumina} + .7 \text{ percentage iron oxide}}{\text{Percentage lime} + 1.4 \text{ percentage magnesia}},$$

we have

$$\text{Cementation Index} = \frac{(2.8 \times 18.47) + (1.1 \times 5.73) + (.7 \times 3.29)}{(68.19) + (1.4 \times 2.66)}$$

$$= \frac{51.716 + 6.303 + 2.303}{68.19 + 3.724}$$

$$= \frac{60.322}{71.914}$$

$$= .839.$$

As will be seen later, this is a very typical value for the Cementation Index of a good hydraulic lime.

The use of the Cementation Index, as here stated, involves certain assumptions as to the constitution of hydraulic cementing materials. These are, in order of importance:

(1) That in hydraulic limes and cements the hydraulic activity is due to the formation during manufacture of certain compounds of lime and magnesia with silica, alumina, and iron.

(2) That the silica combines normally with the lime in such molecular proportions as to form the tricalcic silicate, $3CaO \cdot SiO_2$.

(3) That the alumina combines with the lime as the dicalcic aluminate, $2CaO \cdot Al_2O_3$.

(4) That magnesia is, molecule for molecule, equivalent to lime in its action.

(5) That iron oxide is, molecule for molecule, equivalent to alumina.

Of these five assumptions, the first is simply a general statement of conditions which are recognized by everybody as probably existing. The second assumption, likewise, is generally accepted, since it agrees with the views of both Le Chatelier and Newberry. The third, based on Newberry's experiments and confirmed by those of Richardson, is practically accepted by all American cement chemists, though not by those who follow Le Chatelier.

The fourth and fifth assumptions, however, are open to question, and the writer realizes that serious objections may be urged against them. But he also realizes that magnesia and iron must be accounted for in some way, that the assumptions above made are inherently probable, and that the resulting "Cementation Index" works out very well in practice. For the present, therefore the "Cementation Index" will be accepted as a guide in discussing the composition and the characteristics of the hydraulic limes.

Use of the Cementation Index in Classification.—The Cementation Index will be used in classifying the various hydraulic products, for it gives information of value concerning the properties of the various products. But it cannot be the sole basis for classification, because the properties of a hydraulic cementing material will be later seen to depend not only on its composition, but on the conditions of its manufacture. A material having a Cementation Index of 1.05 might be, for example, a hydraulic lime, a natural cement, or a cement of the Portland type, depending chiefly on the temperature at which the raw material was burned. In general, however, the possible variation is by no means so wide as this. A material with a Cementation Index of 0.40, for example, could under no possible temperature conditions yield anything but a somewhat weak hydraulic lime.

In later chapters, when the separate products are under discussion, their respective Cementation Indexes will be determined and stated. At present we are only concerned with determining the limiting values of this index for the hydraulic limes. As will be seen from following paragraphs, these limits are theoretically very wide, but in actual practice very narrow.

Definition of hydraulic limes.—The *hydraulic limes* include all those cementing materials (made by burning siliceous or argillaceous limestones) whose clinker after calcination contains so large a percentage of lime silicate (with or without lime aluminates and ferrites) as to give hydraulic properties to the product, but which at the same time contains normally so much free lime (CaO) that the mass of clinker will slake on the addition of water.

The commercial advantage of manufacturing a material of this kind is that, while the product has hydraulic properties, yet its clinker will slake and pulverize itself on the simple addition of water, thus avoiding the expensive mechanical grinding required by the clinker of natural and Portland cements.

The definition, therefore, requires that a material to be called a hydraulic lime must satisfy two conditions: (1) its clinker must contain enough free lime to slake with water, and (2) the resulting powder must be capable of setting or hardening under water. These two requisite conditions, in their turn, fix the limits of lime that the clinker may contain. The *minimum* amount of lime present is obviously determined by the consideration that, after burning, enough free lime (in addition to that combined with the silica, alumina, and iron) must be present in the clinker to reduce the entire mass to powder by the force of its own slaking. The *maximum* amount of lime, on the other hand, is determined by the commercial condition that no more free lime should be present than is absolutely necessary to accomplish this pulverization, for the free lime, whose slaking powders the mass, is by that same slaking made into an inert, or at least non-hydraulic, material.

The desired result—the formation of a clinker consisting largely of lime silicates, etc., but also containing sufficient free lime to slake readily—can be attained in two different ways, which yield products very different in quality. These two methods are:

(1) By the calcination, at a medium temperature, of a siliceous or argillaceous limestone having a Cementation Index lying between 0.30 and 1.10. Such a limestone will carry so high a percentage of calcium carbonate (relative to its content of silica, alumina, and iron oxide) as to leave, after *most* of its silica, etc., have been combined with lime,

sufficient free lime to slake the clinker. Hydraulic limes produced in this fashion are the *typical* hydraulic limes, and the following chapters will have reference to such materials only. It is possible, however, to produce a hydraulic lime by another method, as above noted. This second and much less satisfactory method is

(2) By the calcination, at temperatures too low to permit perfect combination of the silica, alumina, and iron oxide with the lime, of a siliceous or argillaceous limestone (less rich in lime than those employed in the first method) having a Cementation Index of 1.10 to 1.60 or over. In other words, a rock is used which would, under proper conditions of burning, give a good natural cement. If it is burned at too low a temperature to effect this, however, the result will be a hydraulic lime, for the clinker will consist partly of silicate and aluminate of lime, together with notable amounts of free lime, free silica, and free alumina. Hydraulic limes produced in this way necessarily carry a very large proportion of absolutely inert material. They are, in fact, simple imperfectly burned natural cements and will not be discussed further in this connection.

Reverting to the true hydraulic limes, it has been said above that their Cementation Index may range from 0.30 to 1.10; and it will be seen later that commercial hydraulic limes do occur with indexes as low as 0.331, while others are as high as 1.06.

There is, however, considerable reason for dividing the true hydraulic limes into two groups, the first or *eminently hydraulic limes* containing those products whose index lies between 0.70 and 1.10; while the second group, or *feebly hydraulic limes*, contains products whose Cementation Index ranges from 0.70 down as low as 0.30. Commercial as well as theoretical differences serve to separate the two groups, and for that reason they will be discussed in separate chapters. Curiously enough, each of the two classes has an attendant secondary product to be considered. The eminently hydraulic limes during their calcination produce a by-product (grappiers) which is usually marketed separately as a "*grappier cement.*" The feebly hydraulic limes on the other hand are often treated with sulphuric acid in such a way as to develop new properties, and are then marketed as *selenitic limes.* In further discussion of the hydraulic limes, therefore, they will be treated as two groups in two separate chapters, covering respectively

Chapter XIV. Eminently Hydraulic Limes: Grappier Cements.

Chapter XV. Feebly Hydraulic Limes: Selenitic Limes.

CHAPTER XIV.

EMINENTLY HYDRAULIC LIMES: GRAPPIER CEMENTS.

THE hydraulic limes are usually, compared to Portland or good natural cements, only feebly hydraulic. This fact, taken in connection with the abundance of materials suitable for the manufacture of natural cements, has prevented the introduction of hydraulic-lime manufacture into the United States, though in Europe the industry is of considerable importance. No hydraulic lime is at present made in this country. A considerable amount of hydraulic lime and grappier cement is, however, annually imported. This is brought about by the fact that these products, being low in iron and soluble salts, are light colored and do not stain masonry. There is thus a fair market for them for architectural rather than for engineering uses. A prominent brand of grappier cement much used in the United States as a "non-staining cement" is called Lafarge.

The manufacture and properties of the hydraulic limes and grappier cements will be discussed briefly. This discussion will be practically confined to the practice followed at Le Teil, France, where the largest and best-known plants are located.

Composition of the ideal hydraulic lime.—The clinker of an ideal hydraulic lime should, as may be deducted from the considerations set forth in the preceding chapter, satisfy two limiting conditions. On the one hand, it must contain sufficient free lime to disintegrate the entire mass of clinker by the force of its own slaking. On the other hand, no more free lime should be present than is absolutely necessary to effect this disintegration; and no uncombined silica or alumina should be present in the clinker. This ideal condition would be arrived at, according to Le Chatelier,* if we could obtain a clinker containing four equivalents of lime for one of silica. Three of the four equivalents of lime would be united with all the silica to form tricalcic silicate, while the fourth equivalent of lime would remain free, and would be sufficient to accomplish the disintegration of the entire mass, through the force produced during its own slaking. Accepting this statement,

* Trans. Am. Inst. Min. Eng., vol. 22, p. 16.

we can calculate the percentages of the various constituents which should be present in an ideal hydraulic lime, both before and after slaking, and also the composition of the limestone necessary to give, in burning, this ideal product. The results of such a calculation are shown in the following table:

TABLE 74.

COMPOSITION OF IDEAL HYDRAULIC LIMESTONE AND HYDRAULIC LIME.

	Hydraulic Limestone Before Burning.	Hydraulic Lime.	
		Before Slaking.	After Slaking.
SiO_2.....	13.20	21.20	19.08
CaO.....	86.8	78.80	70.92
CO_2.....		0.00	0.00
H_2O.....	0.00	0.00	10.00
	100.00	100.00	100.00
Index.....	0.753	0.753	0.753

In actual practice, however, it is found that these theoretical compositions cannot be worked up to advantageously. If, for example, a limestone of the composition given above (SiO_2 13.2 per cent, $CaCO_3$ 86.8 per cent) is burned under the ordinary conditions of hydraulic-lime manufacture, it is found that all the silica does not combine with three fourths of the lime, as is required by the theory. What actually happens is that part of the silica will combine with part of the lime to form tricalcic silicate, thus leaving a certain amount of uncombined silica and entirely too much uncombined lime. Any increase in the uncombined lime beyond the amount necessary to cause the clinker to disintegrate by its slaking lessens the hydraulic value of the product.

It is therefore necessary, in practice, to modify the ideal compositions, these modifications being in the following directions:

(*a*) *Lower lime content.* The limestones in actual use, as shown by the analyses quoted in Tables 75 and 76, differ from the ideal hydraulic limestone in carrying from 70 to 80 per cent of lime carbonate in place of the 86.8 per cent of theory. This lowering in the original lime carbonate content of the limestones decreases the amount of uncombined lime in the product.

(*b*) *Presence of alumina and iron.* Even the best hydraulic limestones in actual use carry notable amounts of alumina and iron oxide. These constituents act as fluxes, facilitating the combination of the silica and lime. They also combine themselves with lime to form

aluminates and ferrites of lime. These latter salts do not increase the hydraulic value of the product, for they become hydrated and inert during the process of slaking, but their formation disposes of some of the excess of free lime.

The effect of these modifications is shown clearly when the Cementation Indexes of the ideal and the various commercial products are computed and compared. Le Chatelier's ideal lime has a Cementation Index of 0.75, while the actual limes whose analyses are given later will average about 0.85.

Analyses of a number of commercial hydraulic limes are given in Table 79, page 183.

Raw materials: hydraulic limestones.—The limestones actually used in the manufacture of hydraulic limes will carry from 70 to 80 per cent of lime carbonate. In hydraulic limestones of the best types, such as are used at Le Teil, France, the silica will vary between 13 and 17 per cent, while the alumina and iron together rarely exceed 3 per cent.

TABLE 75.

ANALYSES OF HYDRAULIC LIMESTONES, LE TEIL, FRANCE.

	1.	2.	3.	4.
Silica (SiO_2)	12.40	13.75	16.89	14.30
Alumina (Al_2O_3)	0.60	0.65	0.81	0.70
Iron oxide (Fe_2O_3)	0.50	trace	trace	0.80
Lime (CaO)	47.49	47.00	45.40	46.50
Magnesia (MgO)	n. d.	n. d.	n. d.	n. d.
Carbon dioxide (CO_2)	37.31	36.93	35.67	36.54

1. Alignole quarry; average of six analyses by Rivot.
2. Gaillant quarry; average of three analyses by Rivot.
3. Tinlière quarry: analyses by Rivot.
4. Lafarge quarry; average of nine analyses by Rivot.

TABLE 76.

ANALYSES OF HYDRAULIC-LIME ROCKS, FRANCE AND GERMANY.

	1.	2.	3.	4.
Silica (SiO_2)	17.00	11.60	11.03	11.20
Alumina (Al_2O_3)	1.00	3.60	3.75	5.30
Iron oxide (Fe_2O_3)	.....	3.0	5.07	4.60
Lime (CaO)	44.80	42.84	43.02	35.50
Magnesia (MgO)	0.71	1.43	1.34	5.85
Carbon dioxide (CO_2)	35.99	35.23	35.27	34.35

1. Senonches, France. Descotils, analyst.
2. Metz, France. Berthier, analyst.
3. Hausbergen, Germany. Muspratt, analyst.
4. Plassac, France. Vicat, analyst.

Quoted by Zwick, "Hydraulischer Kalk und Portland-Cement," pp. 66, 67.

TABLE 77.

ANALYSES OF THE VARIOUS BEDS IN THE HYDRAULIC LIMESTONE QUARRIES AT MALAIN, FRANCE.

	1.	2.	3.	4.	5.	6.	7.	8.	9.
Silica (SiO_2)	7.60	10.15	10.30	12.30	15.70	13.80	14.20	14.25	14.70
Alumina (Al_2O_3), Iron oxide (Fe_2O_3)	0.75	0.90	0.65	1.00	1.10	0.80	0.85	0.75	0.60
Lime (CaO)	50.05	48.05	48.30	46.90	44.75	46.30	45.75	45.35	45.05
Magnesia (MgO)	0.30	0.30	0.30	0.25	0.20	0.25	0.40	0.40	0.30
Carbon dioxide (CO_2), Water	41.30	40.60	40.45	39.55	38.25	38.85	38.80	39.25	39.35
Cementation Index	.....	.....	0.739						

	10.	11.	12.	13.	14.	15.	16.	17.	18.
Silica (SiO_2)	14.75	16.35	16.10	16.80	14.90	14.35	12.45	14.85	6.40
Alumina (Al_2O_3), Iron oxide (Fe_2O_3)	1.05	1.00	0.80	0.30	0.80	0.80	0.70	0.75	0.45
Lime (CaO)	45.15	43.85	44.20	44.60	45.10	45.55	46.80	45.15	51.05
Magnesia (MgO)	0.15	0.55	0.40	0.40	0.45	0.40	0.45	0.45	0.45
Carbon dioxide (CO_2), Water	38.90	38.25	38.50	37.90	38.75	38.90	39.60	38.80	41.65
Cementation Index	.....	1.05							

Burning.—Hydraulic lime is burned in continuous kilns, like common lime. No difference, in fact, exists between the burning of common and of hydraulic limes, so far as the practical operations involved are concerned. The temperature attained in burning is, however, higher in hydraulic lime-kilns than in those burning common lime, and the fuel requirements are correspondingly increased. Beckwith states, for example, that at Teil 100 tons of coal are required to burn stone equivalent to 500 tons of screened lime. This corresponds to a fuel consumption of 20 per cent by weight on the lime production.

The temperature and thoroughness of the burning are directly related to the Cementation Index of the lime. The higher the index the less care will be necessary to avoid the presence of too much free lime. A hydraulic lime of index 0.75, for example, would be much more difficult to burn properly than one whose index ran as high as 0.85 or so. In fact, as the index approaches 1.00, the difficulty is, not to avoid free lime, but to keep enough free lime in the product to enable it to slake properly.

In Tables 78 and 79 are given the analyses of a number of hydraulic limes, after being burned but before slaking.

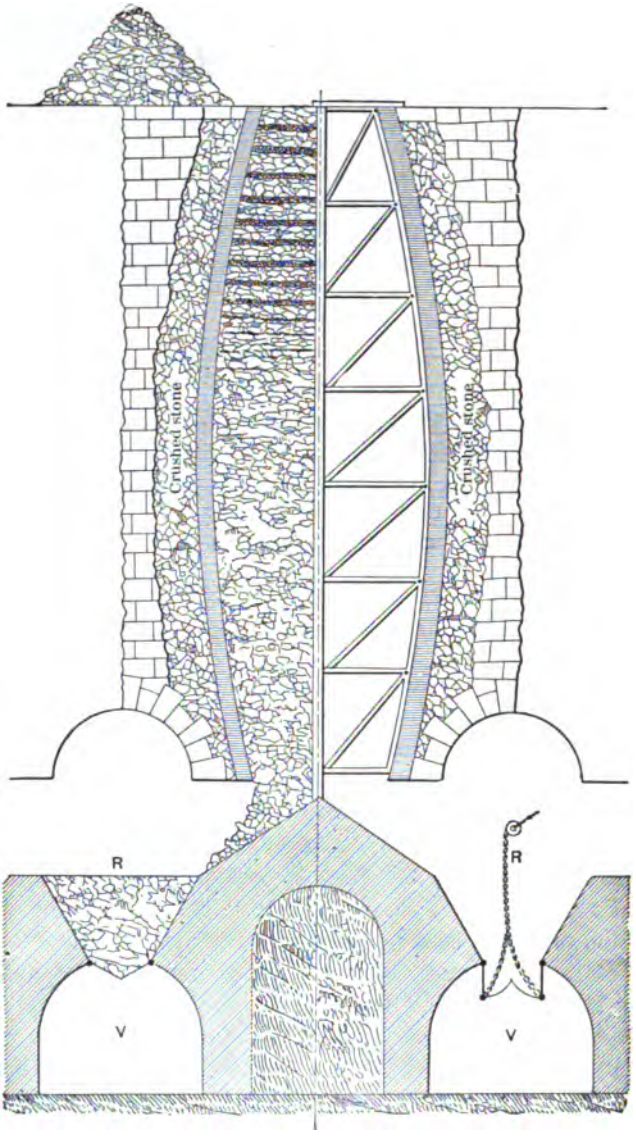

FIG. 30.—Kiln used for burning hydraulic lime, Malain, France. (After Bonnami.)

TABLE 78.

ANALYSES OF HYDRAULIC LIME BEFORE SLAKING (LE TEIL, FRANCE).

	1.	2.	3.	4.	5.	6.	7.	8.	9.
Silica (SiO_2)	20.33	22.39	23.60	22.95	20.57	21.7	26.07	26.4	22.59
Alumina (Al_2O_3)	1.00	1.06	1.28	1.12	1.13	1.8	4.38	} 3.0	{ 2.63
Iron oxide (Fe_2O_3)	0.82	tr.	tr.	1.28	tr.	0.6	tr.		{ 0.84
Lime (CaO)	77.87	76.55	75.12	74.64	77.76	74.0	68.94	65.16	65.62
Magnesia (MgO)	n. d.	n. d.	n. d.	n. d.	0.54	0.7	0.61	1.04	1.54
Cementation Index	0.753	0.834	0.898	0.899	0.749	0.842	1.115	1.155	0.985

1. Average of lime burned from Alignole quarry rock.
2. " " " " " Gailliant quarry rock.
3. " " " " " Tinlière quarry rock.
4. " " " " " Lafarge quarry rock.

} Analyses by Rivot. Quoted by Zwick, "Hydraulischer Kalk und Portland-Cement," pp. 67, 69.

5. Analysis by Vicat. Quoted by Beckwith, "Hydraulic Lime of Teil," p. 13.
6. Quoted by Stanger and Blount, Mineral Industry, vol. 5, p. 70.
7. Analysis by Vicat. Quoted by Beckwith, "Hydraulic Lime of Teil," p. 13.
8. Analysis by Landrin. Quoted by Thorpe, "Dictionary Applied Chemistry," vol. 1, p. 483.
9. Analysis by Michaëlis. Quoted by Schoch, "Mörtel-Materialen," p. 73.

Two of the above analyses of Teil lime, Nos. 7 and 8, give exceptionally high values for the Cementation Index. The average index of all nine samples is 0.913; if Nos. 7 and 8 be excluded the average is 0.85.

TABLE 79.

ANALYSES OF HYDRAULIC LIMES, FRANCE, GERMANY AND ENGLAND.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	26.77	18.47	17.18	17.75	23.61	24.33
Alumina (Al_2O_3)	1.57	5.73	5.84	8.88	3.89	3.73
Iron oxide (Fe_2O_3)	.....	3.29	6.32	6.18	.....	n. d.
Lime (CaO)	70.54	68.19	68.56	56.01	71.99	71.94
Magnesia (MgO)	1.12	2.66	2.09	9.28	0.51	n. d.
Cementation Index	1.06	0.839	0.839	0.925	0.968	1.00

1. Senonches, France. Descotils, analyst.
2. Metz, France. Berthier, analyst.
3. Hausbergen, Germany. Muspratt, analyst.
4. Plassac, France. Vicat, analyst.
5. d'Emondeville, France. Vicat, analyst.

} Quoted by Zwick, "Hydraulischer Kalk und Portland-Cement," pp. 766–6.

6. Lyme Regis, England. Quoted by Cummings, "American Cements," p. 35.

Slaking.—Hydraulic lime, after burning, is a mixture of two distinct compounds. Part of the mass is composed of lime silicate, which would not slake if water were poured on it, but would form a hydraulic cement if finely ground. The remainder of the hydraulic lime consists simply of quicklime, which *will* slake with water.

The result of the mixture of the two ingredients is that if water be poured on a lump of hydraulic lime the portion consisting of quicklime will rapidly take up the water and slake. In its slaking its expansion will break up the entire mass into a fine powder. If this operation be done carefully, with just the proper amount of water, the result will be a fine, dry, white powder, consisting mostly of lime silicate with about one-third to one-fourth as much of slaked lime.

In the earlier days of hydraulic-lime manufacture in France (and even at the present day in England) it was the practice to put the hydraulic lime on the market in lumps, just as it is drawn from the kiln, leaving the work of slaking it to the purchaser. At present, however, the slaking in the French works is done at the lime-plant. The advantages of this method of procedure are that (1) the slaking is done more uniformly and carefully, so that the value and reputation of the lime is improved, and (2) the lime gains considerably in weight and bulk during slaking, so that the cost of slaking is made up.

Slaking should be done with as little water as is compatible with thorough slaking. The lime as drawn from the kiln is therefore spread out in thin layers and lightly sprinkled with water. It is then shoveled up into heaps or into bins, where it is allowed to remain for ten days or so. The slaking is completed, while the lime is thus heaped up, by the aid of the steam which is generated.

After slaking is completed, the lime remains as a fine powder interspersed with lumps (grappiers) of harder material. These lumps consist in part of lime silicate and in part of unburned or underburned limestone. It would be desirable if practicable to remove the latter material, as it is, of course, valueless as a cement. The lumps of lime silicate, on the contrary, will, if finely ground, make a good natural cement. This separation is, however, commercially impracticable, and therefore all the grappiers are treated together.

The lime after slaking is passed over screens (of about 50-mesh). These screens permit all the slaked lime to pass, but reject the grappiers. The lime is sent to the packers, while the grappiers are ground finely under millstones. A certain percentage of ground grappiers is usually added to the lime, in order to increase its hydraulicity. The grappiers alone are also sold as a cement.

The analyses by Durand-Claye, given in Table 80, are quoted in Spalding's " Hydraulic Cements," p. 20, and serve to illustrate the composition of the various products.

In this series analysis No. 1 is of the lime which has completely powdered during slaking and passed through the first sieve, while analysis No. 3 is of the grappiers rejected by this sieve. It will be seen that while the slaked lime has a Cementation Index of 0.992, the grappiers are proportionately less rich in lime (CaO), having an index of 1.63. In order to increase the hydraulic properties of the lime which has passed the sieve, a certain proportion of ground grappiers is added to it. This causes the lime as marketed to have a Cementation Index of 1.08, as shown by analysis No. 2, which is of the Teil lime in its

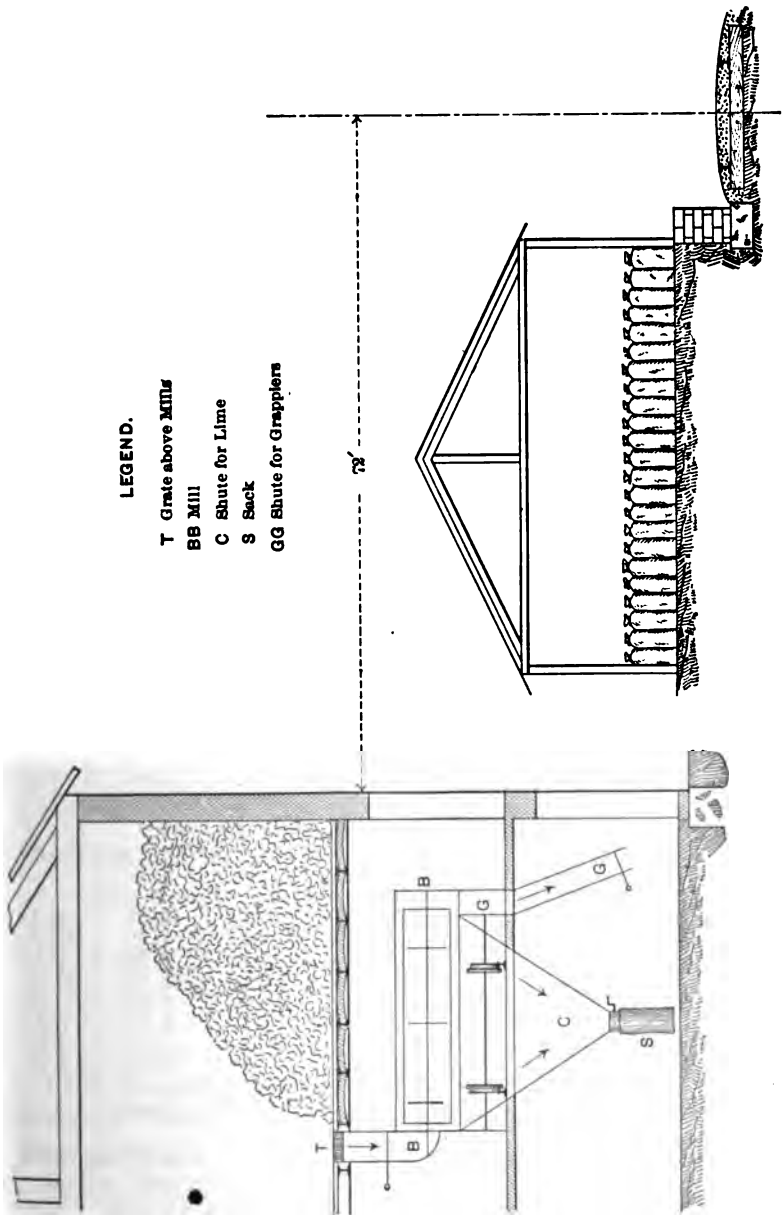

FIG. 31.—Section of hydraulic lime-plant at Malain, France. (After Bonnami.)

commercial form. During the burning a small percentage of a third compound close in composition to $CaO \cdot SiO_2$ is formed. This product is not used in either the hydraulic-lime or grappier-cement industries, but is mixed with slaked lime and used in the manufacture of pipe, tile, etc. It is, in fact, an artificial puzzolana, as is seen from its analysis (No. 4), which gives a Cementation Index of 2.82.

TABLE 80.

ANALYSES OF KILN PRODUCTS, TEIL, FRANCE.

	1.	2.	3.	4.
Silica (SiO_2)	23.05	23.95	31.85	43.90
Alumina (Al_2O_3)	2.75	3.10	4.25	8.20
Iron oxide (Fe_2O_3)				
Lime (CaO)	65.75	63.35	55.60	45.25
Magnesia (MgO)	1.50	1.15	1.20	0.85
Water, etc	6.95	8.50	7.10	2.60
Cementation Index	0.992	1.08	1.63	2.82

These analyses by Durand-Claye have been used because they form a complete series. They are not entirely representative, however, of Teil hydraulic lime, as is seen on comparing them with analyses No. 2 and 3 in Table 81, below. These latter analyses give Cementation Indexes of 0.841 and 0.854 respectively, which are considerably lower than of the corresponding analyses of Table 80.

TABLE 81.

ANALYSES OF HYDRAULIC LIMES, AFTER SLAKING.

	1.	2.	3.
Silica (SiO_2)	22.0	19.05	18.2
Alumina (Al_2O_3)	2.0	1.6	1.2
Iron oxide (Fe_2O_3)	2.0	0.55	0.8
Lime (CaO)	62.0	65.10	60.0
Magnesia (MgO)	1.5	0.65	1.32
Sulphur trioxide (SO_3)	0.5	0.3	n. d.
Carbon dioxide (CO_2)	0.0	12.45	8.00
Water	10.0		n. d.
Cementation Index	1.016	0.841	0.854

1. Typical hydraulic lime, after slaking. Le Chatelier, Trans. Am. Inst. Min. Engrs., vol. 22, p. 16.
2. Hydraulic lime of Teil, after slaking. Thorpe, Dict. Applied Chem., vol. 1, p. 474.
3. Hydraulic lime of Teil, after slaking. Gilmore, "Limes, Cements, and Mortars," p. 125.

Weight and specific gravity.—Beckwith states that Le Teil lime in lumps, before slaking, weighs 36¼ lbs. per cubic foot; while slaked

and screened its weight averages about 43 lbs. per cubic foot. According to Schoch,* the hydraulic limes average in specific gravity about 2.9.

Tensile and compressive strength.—The results given in Table 82 are quoted by Schoch * as being fair averages for hydraulic-lime mortars composed of one part lime and three parts sand; kept for seventy-two hours after molding in a moist atmosphere and the remainder of the time under water.

TABLE 82.

AVERAGE STRENGTH OF HYDRAULIC LIMES. (SCHOCH.)

	Pounds per Square Inch.		
	7 Days.	28 Days.	1 Year.
Tension.....	64 lbs.	100 lbs.	299 lbs.
Compression.....	356 "	683 "	1920 "

These results may be compared with those given in Tables 83 and 84, which are quoted by Beckwith as the averages of several series of experiments carried on at Toulon and Marseilles on hydraulic-lime mortars composed of about one part lime to two parts of sand. These mortars were made into blocks and kept under salt water the entire time.

TABLE 83.

TENSILE STRENGTH OF TEIL HYDRAULIC-LIME MORTAR.

Time Immersed.	Tensile Strength in Pounds per Square Inch.						
	1.	2.	3.	4.	5.	6.	Average.
45 days.....	31.71	40.38	30.79	30.83	.....	38.42	34.43
90 "	85.06	88.49	83.78	77.68	57.59	83.77	79.39
180 "	97.11	106.22	89.16	86.88	86.03	94.86	93.38
1 year.....	123.43	111.63	126.42	122.15	121.30	120.94	120.95
2 years.....	141.06	164.20	.....	.....	.....	.....	152.63

Ratio of compressive to tensile strength.—When in use, limes and cements are usually subjected to direct compressive stress only, tensile strains being rarely applied in well-designed and well-built structures. In testing, however, a test for tensile strength is much cheaper and more readily applied than one for compressive strength. The result

* Schoch, C. Die moderne Aufbereitung und Wertung der Mörtel-Materialen. p. 74.

is, that though limes and cements are almost entirely used in compression, they are usually tested in tension. For this reason it is desirable to ascertain, as definitely as possible, the ratio which exists between the compressive and the tensile strength of any type of lime or cement. If this ratio be once determined, a *tensile* test can thereafter be used to determine the *compressive* strength of the material.

TABLE 84.

COMPRESSIVE STRENGTH OF TEIL HYDRAULIC-LIME MORTARS.

Time Immersed.	Compressive Strength in Pounds per Square Inch.				
	1.	2.	3.	4.	Average.
45 days	219.59	191.75	194.09	205.04	202.62
90 "	359.62	362.41	355.20	259.15	334.10
180 "	593.98	467.13	451.34	504.24	504.17
1 year	612.91	591.84	561.87	588.99	588.90
2 years	613.88	577.33	573.92	.....	588.38

In the present case, the tensile and compressive tests given in Tables 82, 83, and 84 have been compared. The results are sufficiently close to indicate that the compressive strength of a hydraulic-lime mortar mixed in the usual working proportions (1 lime to 2 or 3 sand) will be from five to six times the tensile strength of the same mixture. (The actual average value, given by eight tests, for this ratio was 5.38 to 1.)

Proportions for mortars and concretes.—The following proportions for making mortars and concretes with hydraulic lime are recommended by Beckwith:

(*a*) Mortar for use in salt water: $10\frac{1}{2}$ U. S. bushels (590 lbs.) of Teil lime to 1 cubic yard of sand, equivalent to one scant measure of lime to two full measures of sand.

(*b*) Mortar for use in fresh water: 9 U. S. bushels (506 lbs.) of Teil lime to 1 cubic yard of sand, equivalent to $1\frac{3}{4}$ measures of lime to 3 measures of sand.

(*c*) Mortar for use in air: $7\frac{1}{2}$ U. S. bushels (421 lbs.) of Teil lime to 1 cubic yard of sand, equivalent to 1 measure of lime to 3 measures of sand.

(*d*) For concretes the usual proportions are:

(1) For use in salt water, 2 measures mortar to 3 measures of broken stone.

(2) For use in fresh water, 1 measure mortar to 2 measures of broken stone.

Grappier Cements.

Grappier cements are made by grinding finely the lumps of unburned and overburned material which remain when a hydraulic lime is slaked. These lumps, as earlier noted, consist partly of lime silicate and partly of unburned limestone. The value of the resulting grappier cement will depend on the proportions in which these two ingredients occur in the lumps. If lime silicate forms most of the lumps, the grappier cement will be a very satisfactory material, approximating to Portland cement in its properties. If most, or even a large part, of the lumps consist of unburned limestone, however, the grappier cement will be practically worthless.

Lafarge cement, well known on the American market as a "non-staining" cement, is a grappier cement of very satisfactory composition made at Teil, France.

Composition of grappier cements.

TABLE 85.

ANALYSES OF GRAPPIER CEMENTS.

	1.	2.	3.	4.	5.
Silica (SiO_2)	26.5	31.85	31.10	27.38	24.65
Alumina (Al_2O_3)	2.5	4.25	4.43	2.61	6.55
Iron oxide (Fe_2O_3)	1.5		2.15	1.02	2.60
Lime (CaO)	63.0	55.60	58.38	58.38	56.30
Magnesia (MgO)	1.0	1.20	1.09	0.46	0.90
Alkalies (K_2O,Na_2O)	n. d.	n. d.	0.94	n. d.	n. d.
Sulphur trioxide (SO_3)	0.5	n. d.	0.60	0.43	0.35
Carbon dioxide (CO_2)	5.0	7.10	1.28	n. d.	8.65
Water			n. d.	n. d.	
Cementation Index	1.212	1.63	1.560	1.359	1.356

1. Typical grappier cement. Le Chatelier, Trans. Amer. Inst. Min. Engrs., vol. 22, p. 19.
2. Teil grappiers. Analysis by Durand-Claye. Quoted by Spalding, "Hydraulic Cement," p. 20.
3. Lafarge cement. C. F. McKenna, analyst, 1897. Sales-agents' circular.
4. Lafarge cement. Quoted by E. Duryee, Engineering News, vol. 47, p. 23. Jan. 9, 1902.
5. Malain grappier cement. Quoted by Bonnami, "Fabrication et controle des Chaux Hydrauliques," p. 54.

Physical properties of grappier cements.—The only data available on the strength, etc., of grappier cements are those contained in the circular issued by the American sales-agents of the Lafarge brand. The tests were conducted in 1897 by Dr. C. F. McKenna.

The Lafarge cement gave the following results:

Specific gravity, not ignited	2.6	Initial set	4 hours
" " ignited	2.7	Final set	10 hours
Loss on ignition	3.83%	Fineness	99.9% through 50-mesh
		"	99.4% through 100- "

TABLE 86.

TESTS OF TENSILE STRENGTH, LAFARGE CEMENT. (MCKENNA.)

Composition of Mortar.	Tensile Strength in Pounds per Square Inch.						
	1 Week.	1 Month.	3 Months.	7 Months.	8 Months.	1 Year.	2 Years.
Neat cement, 22½% water.....	330	465	500	...	...	...	665
Neat cement, 24% water.....	320	...	....	542	...	645	665
1 part cement, 2 parts sand....	145	242	298	...	470		

These results have been plotted diagrammatically, as shown in Fig. 32.

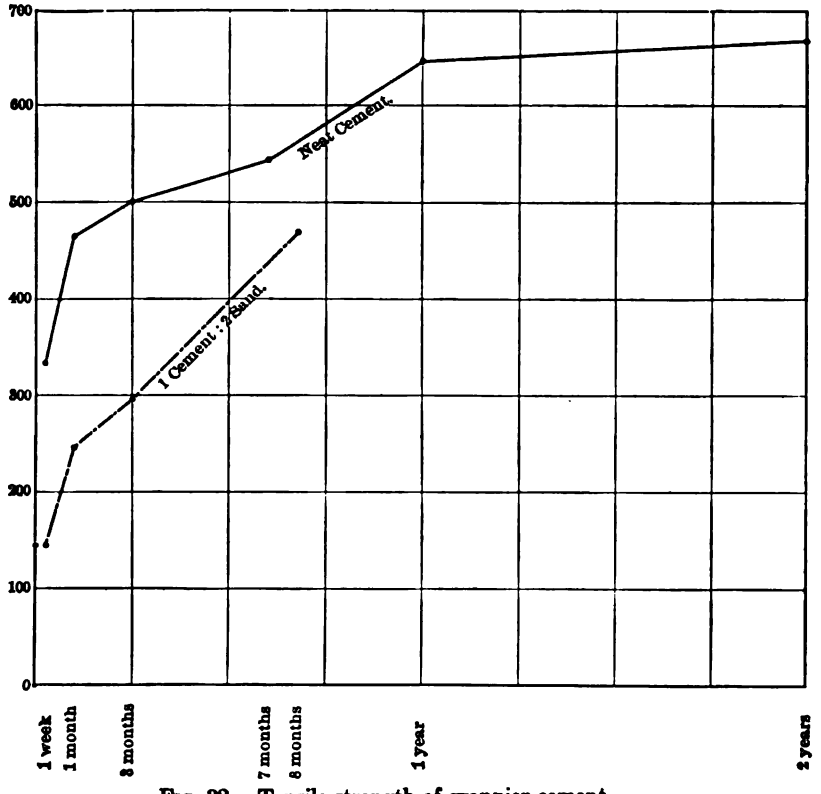

FIG. 32.—Tensile strength of grappier cement.

Later experience and tests.—The foregoing pages relative to hydraulic limes and grappier cements have been allowed to stand unchanged, since in the light of present knowledge it can be seen that

they contain no serious errors or misstatements. But our experience in France during the World War justifies further details concerning both products, because they are in reality of far more technical value and importance than I thought in 1905. Since that date the American army used some 20,000 tons of hydraulic lime and grappier cement in its various constructions in France;* and for my own part, owing to the fortunes of war, I had for some time to operate the largest mills of that sort in Europe—the Le Teil plants described on earlier pages of this volume.

With regard to hydraulic limes I would say now that they have two important advantages; they cost no more to make than ordinary quicklimes, while they are about as good as natural cements. In sea-water, as is well known, the better grades of hydraulic limes seem to outclass Portland cements for resistance to chemical attack. For ordinary structural uses they are of course limited by their slow hardening and relatively low tensile strength. They can not therefore be used for reinforced concrete or other critical work; but for foundations and other mass-concrete they are good enough and very cheap.

The grappier cements are far superior products, and are again far cheaper to make than Portland cements. Their value is not shown in neat short-time tests, but in long-time mortar tests. I have averaged two very long series of tests by Leduc, one on French Portlands and one on French hydraulic lines, with the following comparative results (Table 87). The value of this comparison is, of course, that the tests were not made to prove any special point; they were the ordinary run of materials that Leduc handled during many years at the Laboratory of Arts et Métiers in Paris.

TABLE 87.

COMPARATIVE TESTS OF GRAPPIER AND PORTLAND CEMENTS (LEDUC).

Age.	Portland Cement, Neat, Pounds per Square Inch.	Portland Cement, 1 : 3, Pounds per Square Inch.	Grappier Cement, Neat, Pounds per Square Inch.	Grappier Cement, 1 : 3, Pounds per Square Inch.
1 week	455	142	242	114
4 weeks	654	199	356	185
12 weeks	768	256	498	285
26 weeks	796	313	555	356
1 year	740	327	569	412
2 years	868	370	569	441

* Eckel, E. C. The cement supply, American Expeditionary Forces. Concrete, Nov., 1921, et seq.

From this it will be seen that the neat Portland is superior to the neat grappier cement at all periods tested, though its lead falls off somewhat in the long-time tests. The grappier mortar, however, though showing low results at one month and less, passes the Portland mortar at longer periods. Since a grappier cement costs normally not much more than half as much as Portland cement, the importance of these facts is obvious.

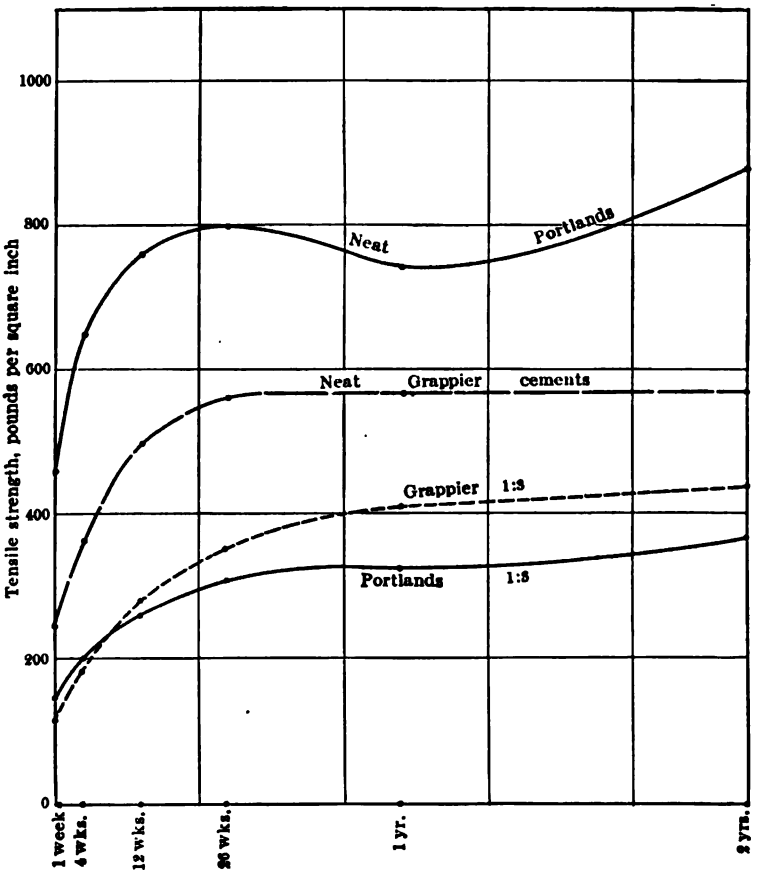

FIG. 33.—Tensile strength of grappier *vs.* Portland cements. (Leduc.)

References on hydraulic limes and grappier cements.—The following list contains the more important modern books and papers dealing with these subjects in any detailed way, together with the original work of Vicat, on which all modern cement manufacture has been founded.

Bied et Lacarme. Chaux Hydrauliques et Ciments de Lafarge. 8vo, pp. 472. Paris, 1914.

Beckwith, L. F. The hydraulic lime of Teil. 8vo, pp. 78. New York, 1873.

Bonnami, H. Fabrication et controle des chaux hydrauliques et des ciments. 8vo, pp. 276. Paris, 1888.

Candlot, E. Ciments et Chaux Hydrauliques. 8vo, pp. 455. Paris, 1898.

Le Chatelier, H. Experimental Researches on the constitution of hydraulic mortars. 8vo, pp. 132. New York, 1905.

Leduc et Chenu. Chaux, Ciments, Platres. 12mo, 252 pp. Paris, 1912.

Leduc, E. Aide-Mémoire des Industries de Ciment, Chaux, Platre. 12mo, 336 pp. Paris, 1914.

Schoch, Carl. Die moderne Aufbereitung und Wertung der Mörtel-Materialien. 8vo, 300 pp. Berlin, 1896.

Vicat, L. J. Résumé des connaissances des Mortiers. 4to, pp. 149. Paris, 1828.

Zwick, H. Hydraulischer Kalk und Portland Cement. 12mo, pp. 315. Vienna, 1892.

CHAPTER XV.

FEEBLY HYDRAULIC LIMES: SELENITIC LIMES.

THE feebly hydraulic limes have been defined in Chapter XIII as including those products whose Cementation Index ranges between 0.30 and 0.70. This means that in such a product, no matter how high the burning temperature, not over 70 per cent of its total lime (CaO) *can* be in combination with the silica, etc., while if the Cementation Index, as shown by analysis, falls as low as 0.30, only 30 per cent of the total lime can be so combined, even under the most favorable circumstances. As combination can never be theoretically complete, it is safe to say that in the feebly hydraulic limes only from 20 to 60 per cent of their total lime is combined, the remainder being left free and capable of slaking. A product containing so much free lime and so little in the combined form can obviously possess little hydraulicity or strength.

Limes of this class would hardly merit description were it not for the fact that they are the usual type of *English* hydraulic limes, and that they often serve as a basis for making a product—selenitic lime—which requires brief attention.

TABLE 88.

ANALYSES OF FEEBLY HYDRAULIC-LIME ROCKS.

	1.	2.	3.
Silica (SiO_2)	5.00	4.64	7.40
Alumina (Al_2O_3)	4.23	7.08	2.70
Iron oxide (Fe_2O_3)		0.85	5.30
Lime (CaO)	48.65	48.27	40.82
Magnesia (MgO)	1.86	.....	4.52
Carbon dioxide	40.26	37.92	37.06
Cementation Index	0.356	0.443	0.581

1. Holywell, England. Muspratt, analyst.
2. Falhagen, Germany. Pasch, analyst.
3. Horb, Würtemberg. Knauss, analyst.

C A N A
U T A H
C O L O
N E W M E X I C O
A R I Z O N A
Salt Lake City
Denver
Albuquerque
El Paso
Phoenix
Tucson
Los Angeles
San Diego
San Francisco
Sacramento
Reno
Las Vegas
Grand Canyon
Yuma
Colorado River
Rio Grande
Pacific Ocean
Gulf of California
Lower California
Mexico
117°
115°
109°
103°

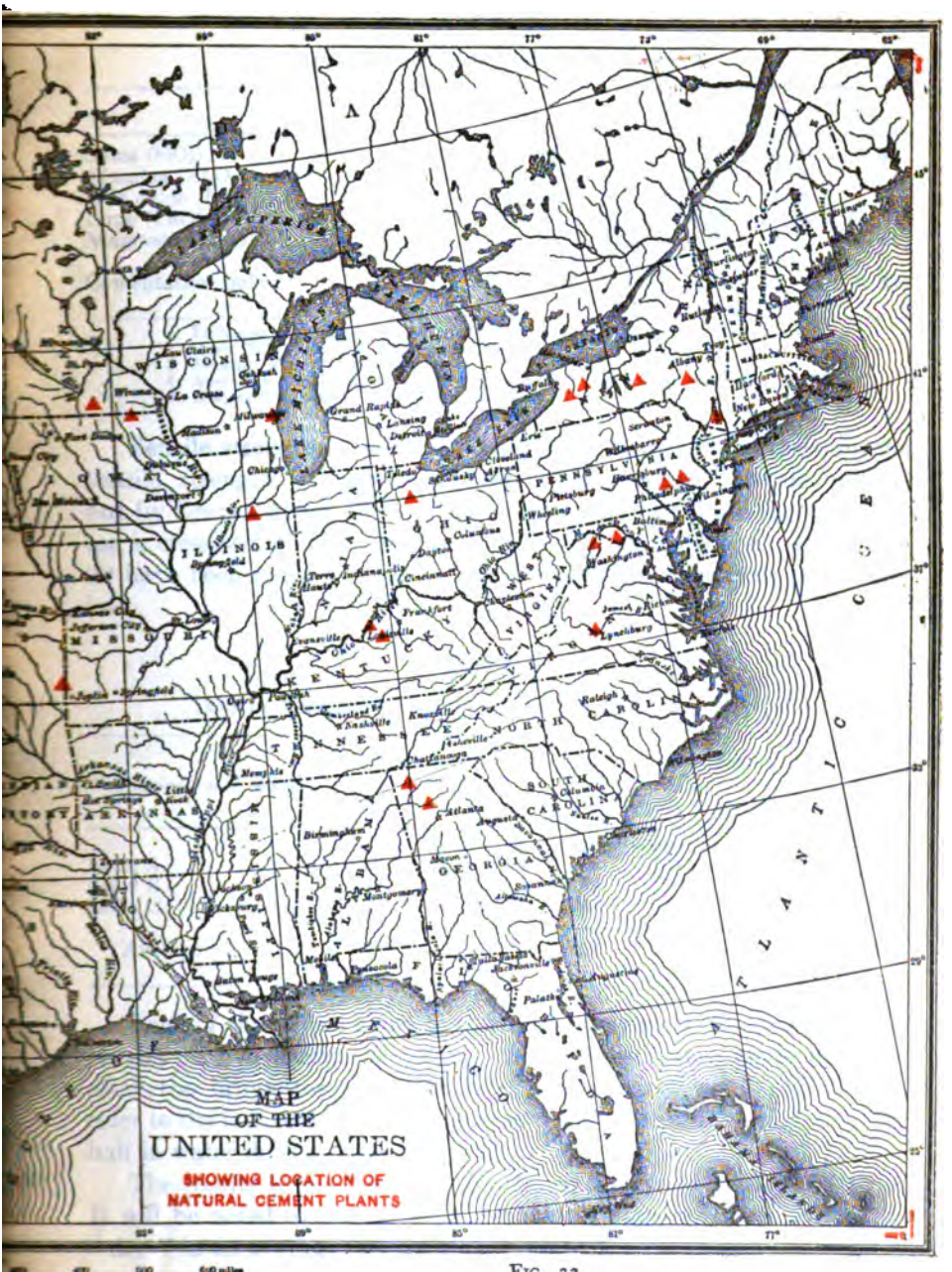

FIG. 33.

[To face p. 194.

TABLE 89.

ANALYSES OF FEEBLY HYDRAULIC LIMES.

	1.	2.	3.	4.	5.
Silica (SiO_2)	7.60	11.95	11.00	16.05	8.36
Alumina (Al_2O_3)	11.60	4.25	3.67	1.92	7.08
Iron oxide (Fe_2O_3)	0.96	8.52	3.00	3.22	
Lime (CaO)	79.09	65.73	78.40	77.29	81.44
Magnesia (MgO)	.....	7.25	3.93	1.52	3.11
Cementation Index	0.429	0.581	0.440	0.621	0.331

1. Falhagen, Germany. Pasch, analyst.
2. Horb, Würtemberg. Knauss, analyst.
3. Fecamp, France. Rivot, analyst.
4. Aberthaw, England. Quoted by Cummings. "American Cements," p. 35.
5. Holywell, England. Muspratt, analyst.

Tensile strength.—In Table 90 are given the results of tests, on the tensile strength of various English hydraulic-lime mortars, carried out by Grant * about 1880. These tests were made on briquettes having a cross-section of $2\frac{1}{4}$ square inches; but the results given in Table 90 have been reduced so as to give the strength in pounds per square inch.

TABLE 90.

TENSILE STRENGTH OF HYDRAULIC-LIME MORTARS. (GRANT.)

Composition of Mortar.	1 Lime: 3 Sand.		1 Lime: 4 Sand.		1 Lime: 5 Sand.		1 Lime: 6 Sand.	
	Dry.	Wet.	Dry.	Wet.	Dry.	Wet.	Dry.	Wet.
	Pounds.	Pounds.	Pounds.	Pounds.	Pounds.	Pounds.	Pounds.	Pounds.
Lime A	50	68	44	57	30	45	21	28
Lime B	48	95	49	59	32	47	23	27
Lime C	40	81	26	61	21	44	18	34
Average	46	81	40	59	28	45	21	30

Each of the values given in this table represents the average of the results on five specimens tested. All the tests were made one year after the briquettes were molded. The words "wet" and "dry" refer to the fact that half of the briquettes were kept in air and the other half in water during the entire year.

The results above tabulated are shown diagrammatically in Fig. 34. It will be noted that the "wet" briquettes gave results exceeding the "dry" in an average ratio of almost 1.6 to 1.

* Proc. Institution Civil Engineers, vol. 62, p. 165. 1880.

Compressive strength.—Tests on the compressive strength of mortars made * from three English hydraulic limes are given in Table 91. These tests were made on 6-inch cubes kept in air for one year before testing. The results have been reduced to give the values for compressive strength in pounds per square inch.

TABLE 91.

COMPRESSIVE STRENGTH OF HYDRAULIC-LIME MORTARS. (GRANT.)

Composition of Mortar.	Kind of Lime.			
	Lime A.	Lime B.	Lime C.	Average.
	Pounds per Square Inch.	Pounds per Square Inch.	Pounds per Square Inch.	Pounds per Square Inch
Lime 1, sand and gravel 6.....	159	178	359	232
" 1, " " " 8.....	72	172	267	137
" 1, " " " 10.....	81	179	133	131

The values given are the average of ten specimens tested.

Selenitic Lime: Scott's Cement.

The cementing material known as Scott's cement, selenitic cement, or selenitic lime consists essentially of lime (CaO) plus a small percentage of sulphur trioxide (SO_3). The lime used as a basis for this cement is always a more or less hydraulic variety, while the sulphur trioxide may be added to it in the form of either plaster of Paris or sulphuric acid. The resulting selenitic lime or Scott's cement shows a markedly higher strength, both in compression and tension, than the lime from which it was made.

Manufacture of selenitic limes.—In his earlier patents Scott provided for the manufacture of this product by exposing lime to the fumes of burning sylphur. This was accomplished † " by reheating calcined lump lime in an oven having a perforated floor, beneath which were placed pots of burning sulphur. The sulphurous-acid fumes from the sulphur rose among the red-hot lumps of lime, leading to the formation of calcium sulphite ($CaSO_3$), and this in turn became oxidized into calcium sulphate ($CaSO_4$). The amount of sulphurous acid thus absorbed by the whole bulk of the lime was small, rarely exceeding from 2 to 5 per cent, and of course only the exterior surfaces of the lumps became coated with the sulphur compound; but when the cement was

* Proc. Institution Civil Engineers, vol. 62, p. 165. 1880.

† Redgrave, G. R. Calcareous cements, p. 176. 1895.

ground, to prepare it for use, the sulphate of lime became evenly distributed throughout the mass.

In course of time General Scott found that he could obtain the same results, either by adding sulphuric acid to the water used in preparing the mortar or by the addition of powdered gypsum or plaster of Paris to the ground lime. It mattered little in what form the sulphuric acid was conveyed to the lime, and many soluble sulphates were found to answer quite as well as the sulphate of lime. Ultimately Scott specified the manufacture of a cement, which he named 'selenitic cement,' by the addition of 5 per cent of ground plaster of Paris to calcined hydraulic lime, which was then ground to an impalpable powder and placed in sacks or casks for use."

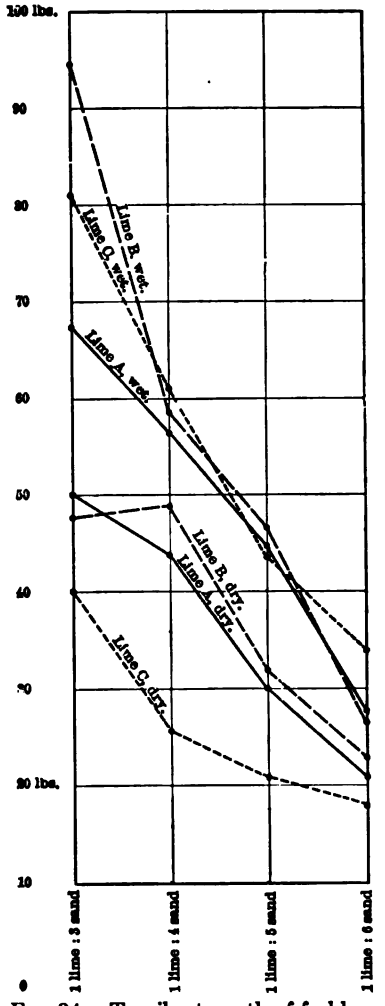

FIG. 34.—Tensile strength of feebly hydraulic limes.

The hydraulic lime used in the manufacture of selenitic lime is apparently always one of the feebly hydraulic varieties such as are discussed earlier in the present chapter.

Tensile strength of selenitic limes. —The following table shows the results of tests * by Grant about 1880 on various selenitic limes. For purposes of comparison tests are also given on two of the limes before the addition of sulphate. The tests were made on briquettes having a sectional area of 2¼ square inches; but in the table below the results given are reduced to pounds per square inch.

Each of the above results represents the average of the tests of five specimens. The tests were made one year after the briquettes were molded. The words " wet " and " dry " refer to the fact that some

* Proc. Institution Civil Engineers, vol. 62, p. 165. 1880.

of the briquettes were kept in air and others in water during the entire year. These results as to tensile strength are shown diagrammatically in Fig. 35.

Compressive strength of selenitic limes.—A number of selenitic limes were tested for compressive strength by Grant, the results being given in Table 93.

The samples discussed in the above table were made up into 6-inch cubes and kept in air one year before testing. The results

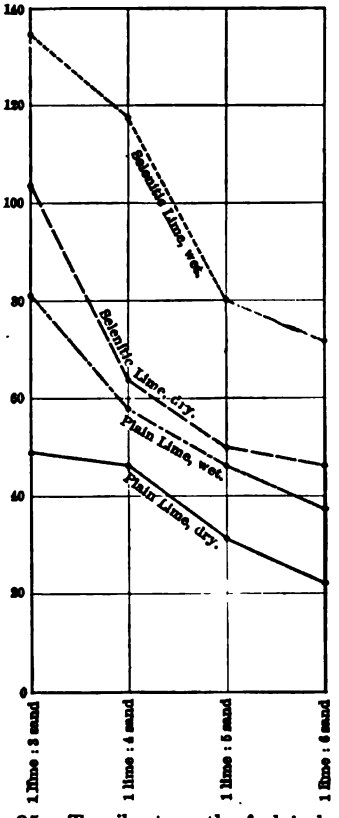

FIG. 35.—Tensile strength of plain hydraulic and selenitic limes.

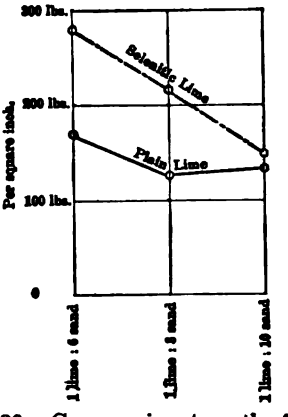

FIG. 36.—Compressive strength of plain hydraulic and selenitic limes.

in the table have been reduced to pounds per square inch.

TABLE 92.

TENSILE STRENGTH OF SELENITIC LIMES. (GRANT.)

	1 Lime: 3 Sand.		1 Lime: 4 Sand.		1 Lime: 5 Sand.		1 Lime: 6 Sand.	
	Dry.	Wet.	Dry.	Wet.	Dry.	Wet.	Dry.	Wet.
A. Gray lime, not selenitic.....	50	68	44	57	30	45	21	28
A'. " " selenitic.....	128	141	65	139	55	87	40	65
B. Lias lime, not selenitic.....	48	95	49	59	32	47	23	27
B'. " " selenitic.....	79	131	63	99	44	72	52	80
C. Selenitic lime.....	123	148	80	129	72	83	58	74
D. " " Rugby.....	91	151	59	102	33	77	29	66
E. " " Aberthaw.....	128	204	83	147	71	123	..	76

TABLE 93.

COMPRESSIVE STRENGTH OF SELENITIC LIMES. (GRANT.)

	1 Lime: 6 Sand.	1 Lime: 8 Sand.	1 Lime: 10 Sand.
A. Gray lime, not selenitic	159	72	81
A'. " " selenitic	289	119	127
B. Lias lime, not selenitic	178	172	179
B'. " " selenitic	268	305	159
C. Selenitic lime	414	239	210
D. " " Rugby	577	533	329
E. " " Aberthaw	530	339	239

The gain in strength due to this process of selenitizing is obvious, but it must be recollected that it gives satisfactory results only when employed on feebly hydraulic limes. With common non-hydraulic limes, and with the better grades of hydraulic limes, the results are not commensurate with the extra expense. For American use, therefore, Scott's process has little to commend it, for our good natural cements would leave little field for such a product as selenitic lime.

References on selenitic limes.—The following brief list comprises the chief papers. Those by General Scott are of course the original references; the citation to Redgrave is given since the original papers may be inaccessible to most readers of this volume.

Graham, Lt.-Col. G. Experiments on Limes and Cements. Prof. Papers, Royal Engrs., vol. 14, new series, pp. 155–161. 1865.

Grant, J. On the Strength of Cement. 8vo, pp. 172. London, 1875.

Redgrave, G. R. Calcareous Cements, pp. 248–253. London, 1905.

Scott, Capt. H. Account of a new cement. Prof. Papers, Royal Engrs., vol. 6, new series, pp. 143–148. 1857.

Scott, Capt. H. Account of the manufacture of a new cement. Prof. Papers, Royal Engrs., vol. 10, new series, pp. 132–158. 1861.

Scott, Capt. H. Observations on Limes and Cements. Prof. Papers, Royal Engrs., vol. 11, new series, pp. 15–94. 1862.

PART V. NATURAL CEMENTS.

CHAPTER XVI.

DEFINITION AND RELATIONS OF NATURAL CEMENTS.

BEFORE taking up a detailed description of the materials, manufacture, and properties of natural cements it will be useful to make some brief general statements concerning the group. In the present chapter, therefore, an attempt will be made to discuss the natural cements as a class, laying emphasis upon the points of resemblance of the various brands and disregarding for a time their many points of difference.

The difficulties which are encountered in such an attempt are greater than the reader, at first sight, may imagine; for few engineers realize what a heterogeneous collection of products is included under the well-known name of "natural cement." The cause of this lack of knowledge is not far to seek. Natural cements are too low in value to be shipped, under ordinary circumstances, far from their point of production. The natural cement made at any given locality has usually, therefore, a well-defined market area within which it is well known and subject to little competition. The engineer practicing within such an area naturally forms his idea of natural cements in general from what he knows of the brands encountered in his work, and as all the brands from one cement-producing locality are apt to resemble one another quite closely, he is likely to conclude that natural cements are quite a homogeneous class, with many points of resemblance and few of difference. The truth is, on the contrary, that there may be far greater differences in strength, rate of set, chemical composition, etc., between the natural cements made in two different localities than between any given brand of natural cement and a Portland cement. This will be brought out clearly in a later chapter, where the composition and properties of the various natural cements will be discussed in considerable detail.

In the present volume the term "natural cements" will be used to include all those cements which are produced by burning, without previous mixing or grinding, a naturally impure limestone rock, i.e., a clayey or argillaceous limestone. As so used the term will include the class of doubtful products commonly known as "natural Portland cements," a class which is quite largely manufactured in Belgium and France. The reasons for including these "natural Portlands" with the natural cements instead of with the true Portlands are stated in detail in a later section of this volume.

The definition of natural cements given on a previous page can be restated here to advantage.

Definition.—Natural cements are produced by burning a natural clayey limestone containing 15 to 40 per cent of silica, alumina, and iron oxide without preliminary mixing and grinding. This burning takes place at a temperature that is usually little, if any, above that of an ordinary lime-kiln. During the burning the carbon dioxide of the limestone is almost entirely driven off, and the lime combines with the silica, alumina, and iron oxide, forming a mass containing silicates, aluminates, and ferrites of lime. In case the original limestone contained any magnesium carbonate the burned rock will contain a corresponding amount of magnesian compounds.

After burning, the burned mass will not slake if water be poured on it. It is necessary, therefore, to grind it quite fine, after which, if the resulting powder (natural cement) be mixed with water, it will harden rapidly. This hardening, or setting, will take place either in air or under water.

Relations of natural cements to others.—Natural cements differ from ordinary limes in two very noticeable ways. These are:

(1) The burned mass does not slake when water is poured on it.

(2) After grinding, natural-cement powder has hydraulic properties, i.e., if properly prepared it will set under water.

Natural cements are quite closely related to both hydraulic limes, on the one hand, and Portland cement, on the other, agreeing with both in the possession of hydraulic properties. They differ from hydraulic limes, however, in that the burned natural-cement rock will not slake when water is poured on it.

The natural cements differ from Portland cements in the following important particulars:

(1) Natural cements are not made by burning carefully prepared and finely ground artificial mixtures, but by burning masses of natural rock.

(2) Natural cements, after burning and grinding, are usually yellow to brown in color and light in weight, their specific gravity being about 2.7 to 3.10, while Portland cement is commonly blue to gray in color and heavier, its specific gravity ranging from 3.0 to 3.2.

(3) Natural cements are always burned at a lower temperature than Portland, and commonly at a *much* lower temperature, the mass of rock in the kiln rarely being heated high enough to even approach the fusing- or clinkering-point.

(4) In use natural cements set more rapidly than Portland cement, but do not attain such a high ultimate strength.

(5) In composition, while Portland cement is a definite product whose percentages of lime, silica, alumina, and iron oxide vary only between narrow limits, various brands of natural cements will show very great differences in composition; while even the same brand, analyzed at different times, will show considerable differences in composition, due to variations in the natural limestone used.

Cementation Index.—In discussing the hydraulic limes (Chapter XIII) attention was called to the desirability of devising some method of general applicability for comparing the hydraulic activity of various cementing materials. The defects of the old "hydraulic index" were pointed out, and a new and more satisfactory index—the Cementation Index—was suggested as a substitute. The value of this innovation will appear in the present section, for in dealing with the natural cements such great variations in composition are found that it is absolutely necessary to have some means of comparing such different products.

The Cementation Index of any limestone or cement is found by applying the following formula:

$$\text{Cementation Index} = \frac{\begin{array}{l}(2.8 \times \text{percentage silica}) + \\ (1.1 \times \text{percentage alumina}) + \\ (.7 \times \text{percentage iron oxide})\end{array}}{(\text{Percentage lime}) + (1.4 \times \text{percentage magnesia})}.$$

When this formula is applied to an unburned limestone it must be recollected that the percentages used in the divisor are those of lime (CaO) and magnesia (MgO) respectively, *not* those of lime carbonate ($CaCO_3$) and magnesium carbonate ($MgCO_3$).

Example of calculation.—The methods of calculating the Cementation Index of any product may be shown by an example, the Utica natural cement whose analysis appears as No. 1, Table 116, p. 244,

being selected for this purpose. The five essential ingredients of that cement, as shown by the analysis, are:

Silica (SiO_2)	19.89
Alumina (Al_2O_3)	11.61
Iron oxide (Fe_2O_3)	1.35
Lime (CaO)	29.51
Magnesia (MgO)	20.38

These values are substituted in the following formula:

$$\text{Cementation Index} = \frac{\begin{array}{c}(2.8\times\text{percentage silica})+\\(1.1\times\text{percentage alumina})+\\(.7\times\text{percentage iron oxide})\end{array}}{(\text{Percentage lime})+(1.4\times\text{percentage magnesia})}$$

$$= \frac{(2.8\times 19.89)+(1.1\times 11.61)+(.7\times 1.35)}{(29.51)+(1.4\times 20.38)}$$

$$= \frac{55.692+12.771+0.945}{29.51+28.532}$$

$$= \frac{69.408}{58.042}$$

$$= 1.19.$$

As will be later seen, this value is fairly characteristic for many natural cements.

Basal assumptions.—It has previously been stated (pp. 174, 175) that the applicability of the Cementation Index depends upon the fact that it is the exact equivalent *in percentage* of a formula which involves the following assumptions:

(1) That the hydraulic activity of any material depends on the formation of certain compounds of lime and magnesia with silica, alumina, and iron oxide.

(2) That in a hydraulic cement, lime combines with silica in such proportions as to form the tricalcic silicate ($=3CaO\cdot SiO_2$); while it combines with alumina in such proportions as to form the dicalcic aluminate ($2CaOSiO_2$).

(3) That in a lightly burned natural cement at least magnesia may be regarded as *molecularly* interchangeable with lime, though of course the differences in their combining weights must be allowed for when the calculation is based on *percentages*.

(4) That iron oxide may, in similar fashion, be regarded as molecularly interchangeable with alumina.

Use of the Cementation Index.—If the assumptions on which the Cementation Index is founded are well based, it is evident that the hydraulic properties—or, rather, the hydraulic *possibilities*—of a product are indicated by its index. A product whose index falls below 1.00 must necessarily contain free lime or free magnesia, whatever the temperature at which it is burned, and such a product should therefore be strictly classed with the hydraulic limes, which require slaking before use. It will be seen later, however, that if a product contains much magnesia (say 20 per cent MgO or over) its Cementation Index may fall below 1.00 without demonstrable defects in the cement. This point is taken up on later pages in discussing the actual composition of various natural cements. A product with an index exceeding 1.00 *can* be burned so as to give complete combination of all its lime and magnesia, leaving none free. As the index increases, the temperature necessary to attain such complete combination decreases, but the hydraulic activity of the product also decreases, until an index exceeding 2.00 indicates a very lightly burned, but also very feeble, cement.

Cementation Index of natural cements.—The term "natural cement" as used in this volume will cover a very large class of cementing products. In the United States the name has become fairly well fixed in use, so that there need be little misunderstanding concerning the limits of the groups. In English and European practice, however, the term "natural cement" has never come into extensive use. It may therefore be necessary to state that, as above defined, it includes the lightly burned but often high-limed cements known to the European trade as "Roman cements," "quick-setting cements," etc., as well as the so-called "natural Portlands."

The differences in composition between the various cements included in this heterogeneous class naturally give rise to corresponding differences in their Cementation Index. It may be said for the group taken as a whole that the Cementation Index of natural cements varies between the limits of 1.00 and 2.00, falling below 1.00 only in the case of certain highly magnesian cements, and that *most* of the natural cements will fall between the narrower limits of about 1.15 to 1.60.

This variation of the Cementation Index may be used as a convenient basis for subdividing the "natural cements" into smaller groups of more homogeneous character.

A. Cements with an index between 1.00 and 1.15. These products when burned at sufficiently high temperature are rather slow-

setting and high in tensile strength, including the " natural Portlands " and allied products. If not burned high enough, however, cements of such low index will necessarily contain large amounts of free lime and magnesia.

B. Cements with an index between 1.15 and 1.60. These include most American natural cements. As the index is higher than in Class A, it is not necessary to burn these products at so high a temperature. Practically all of the European " Roman " cements will also fall in this subgroup.

C. Cements with an index exceeding 1.60. These include the relatively low-limed natural cements, which carry so much clayey material that only a light burning is required in order to combine all their lime and magnesia. As the index rises above 2.00, the products become feebler in hydraulic properties, until at about 3.00 they can be considered only as artificial pozzuolanas.

CHAPTER XVII.

RAW MATERIAL: NATURAL-CEMENT ROCK.

Composition of natural-cement rock.—The raw material utilized for natural-cement manufacture is invariably a clayey limestone carrying from 13 to 35 per cent of clayey material, of which 10 to 22 per cent or so is silica, while alumina and iron oxide together may vary from 4 to 16 per cent. It is the presence of these clayey materials which give the resulting cement its hydraulic properties. Stress is often carelessly or ignorantly laid on the fact that many of our best-known natural cements carry large percentages of magnesia, but it should at this date be realized that magnesia (*in natural cements at least*) may be regarded as being almost exactly interchangeable with lime, so far as the hydraulic properties of the product are concerned. The presence of magnesium carbonate in a natural-cement rock is then merely incidental, while the silica, alumina, and iron oxide are essential. The 25 per cent or so of magnesium carbonate which occurs in the cement rock of the Rosendale district, New York, could be replaced by an equivalent amount of lime carbonate, and the burnt stone would still give a hydraulic product. If, however, the clayey portion (silica, alumina, and iron oxide) of the Rosendale rock could be removed, leaving only the magnesian and lime carbonates, the rock would lose all of its hydraulic properties and would yield on burning simply a magnesian lime.

This point has been emphasized because many writers on the subject have either explicitly stated or implied that it is the magnesium carbonate of the Rosendale, Akron, Louisville, Utica, and Milwaukee rocks that causes them to yield a natural cement on burning. Even a casual consideration of the subject should have recalled to mind the fact that the Cumberland and Lehigh natural-cement rocks are practically free from magnesium carbonate.

A limestone containing sufficient argillaceous matter to make a good natural cement can generally be recognized by the characteristic clayey odor given forth when breathed on.

In determining in advance of actual calcination whether or not

a given rock will make a good natural cement the Cementation Index will prove of service. This can be calculated, as explained on page 204, from the analysis of the rock. If the value of the Cementation Index is over 2.00, the rock will make only a very weak sort of cement, not worth putting on the market as a new product in face of competition from older and stronger brands. If, on the other hand, the Cementation Index is less than 1.00, the rock is in most cases unavailable, for after burning it will contain too much free lime and free magnesia to furnish a safe cement. As noted earlier, however, a rock whose index falls between 0.80 and 1.00 can be made into an apparently safe cement *if it contains 20 per cent or more of magnesia*, by burning at a very high temperature. If the Cementation Index falls between 1.00 and 2.00 it can be assumed that a natural cement of good quality *can* be made from the rock under proper conditions of burning, etc. Within these limits the properties of the cement will vary with the index. A rock with an index of 1.00 to 1.10, for example, will require burning at high temperature, especially if much lime be present (i.e., over 50 per cent CaO). As the index rises, the temperature necessary for burning decreases.

American Natural-cement Rocks.

In the following pages analyses of the rocks used at almost all of the natural-cement plants of the United States will be given. These analyses are thoroughly representative of the raw materials used in the American natural cement industry.

Clayey limestones of the composition required for natural-cement manufacture are very widely distributed, both geologically and geographically, in the United States. There is hardly a State, in fact, in which natural cement of more or less value has not been made at one time or another. In order, however, that a natural-cement industry can become well established in any given locality, certain things are requisite in addition to the occurrence of a good natural-cement rock.

The rock must not only be of the right composition to make a good, sound, and strong cement, but it must be fairly steady in composition, and the beds must be located favorably for cheap extraction of the rock, either by quarrying or by mining. Fuel must also be obtainable at reasonable rates. A good local market and cheap transportation to outside points are necessities.

Of the many localities in the United States at which deposits of good natural-cement rock occur, so few possess the commercial advantages mentioned above that the important natural-cement producing

districts even at the time of maximum expansion of the American industry, were relatively few. As late as 1903, for example, there were still 65 natural-cement plants in operation; of these 20 were in New York State; 15 in the Louisville district of Indiana-Kentucky; 7 in the Lehigh region of Pennsylvania; 4 in Maryland; and 3 in the Utica district of Illinois. The remainder were scattered at various points in Georgia, Kansas, Minnesota, Ohio, Texas, Virginia, Wisconsin, North Dakota and West Virginia.

In the following tables analyses of practically all the rocks used at these localities are presented:

TABLE 94.

ANALYSES OF NATURAL-CEMENT ROCK, UTICA, ILLINOIS.

	1.	2.	3.	4.	5.
Silica (SiO_2)	12.22	17.01	21.00	21.12	14.15
Alumina (Al_2O_3)	9.39	3.35			6.37
Iron oxide (Fe_2O_3)	3.90	2.39	2.00	1.12	2.35
Lime (CaO)	24.40	32.85	24.36	23.66	26.32
Magnesia (MgO)	10.43	8.45	14.31	15.22	12.10
Alkalies (K_2O,Na_2O)	n. d.	n. d.	0.18	n. d.	0.18*
Sulphur trioxide (SO_3)	n. d.	1.81	n. d.	n. d.	1.81
Carbon dioxide (CO_2)	38.48	34.12	34.90	35.35	34.70
Water			3.00	1.07	2.03
Cementation Index	1.21	1.19	.....	.....	1.11

* Far too low; true value is problaby over 4 per cent.

1. F. W. Clarke, analyst. Sample collected by E. C. Eckel.
2. C. Richardson, analyst. Brickbuilder, vol. 6, p. 151. July, 1897.
3. Blaney and Mariner, analysts. "Geology of Illinois," vol. 1, p. 151.
4. Blaney, analyst. Trans. Am. Inst. Min. Engrs., vol. 13, p. 180.
5. Average of preceding four analyses.

TABLE 95.

ANALYSES OF NATURAL-CEMENT ROCK, LOUISVILLE DISTRICT, IND.-KY.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	9.69	9.80	13.65	15.21	18.33	13.36
Alumina (Al_2O_3)	2.77	2.03	3.46	4.07	4.98	3.46
Iron oxide (Fe_2O_3)	1.95	1.40	1.45	1.44	1.67	1.58
Lime (CaO)	29.09	29.40	34.55	33.99	30.41	31.49
Magnesia (MgO)	15.69	16.70	7.97	7.57	8.04	11.19
Carbon dioxide (CO_2)	40.14	41.49	35.92	35.03	32.76	37.07
Cementation Index	0.618	.....	.....	.....	1.39	

Analyses 1-5 inclusive were made by W. A. Noyes. Quoted by Siebenthal, 25th Ann. Rep. Indiana Dept. Geology and Natural Resources, pp. 380-386.

1. Rock used for "Crown" brand, Hausdale mill, New Albany Cement Company.
2. " " " "Fern Leaf" brand, Ohio Valley mill, Ohio Valley Cement Company.
3. " " " "Diamond" brand, Falls City mill, Union Cement and Lime Co.
4. " " " "Star" brand, Speed mill, Louisville Cement Company.
5. " " " "Black Diamond," Black Diamond mill, Union Cement and Lime Co.

TABLE 96.

ANALYSES OF NATURAL-CEMENT ROCK, FORT SCOTT, KANSAS.

	1.	2.	3.	4.
Silica (SiO_2)	15.21	17.26	21.80	18.09
Alumina (Al_2O_3)	4.56	2.05	3.70	3.44
Iron oxide (Fe_2O_3)	n. d.	5.45	3.10	4.27
Lime (CaO)	36.52	34.45	35.00	35.32
Magnesia (MgO)	5.07	5.28	3.50	4.62
Carbon dioxide (CO_2)	34.27	32.87	33.00	33.38
Cementation Index	.....	.....	1.68	

1. Smith, Mineral Industry, vol. 1, p. 49.
2. Brown, "Cement Directory," 2d ed, p. 276.
3. Richardson, Brickbuilder, vol. 6, p. 151. July, 1897.
4. Average of preceding analyses.

TABLE 97.

ANALYSES OF NATURAL-CEMENT ROCKS, CUMBERLAND AND HANCOCK, MARYLAND.

	1.	2.	3.	4.	5.
Silica (SiO_2)	19.81	24.74	27.1	28.72	22.07
Alumina (Al_2O_3)	7.35	16.74		12.28	12.12
Iron oxide (Fe_2O_3)	2.41	6.30	1.5	5.22	3.36
Lime (CaO)	35.76	23.41	36.40	25.54	30.28
Magnesia (MgO)	2.18	4.09	2.52	1.10	2.47
Alkalies (Na_2O, K_2O)	n. d.	6.18	0.3	n. d.	*
Sulphur trioxide (SO_3)	n. d.	2.22	n. d.	1.53	*
Carbon dioxide (CO_2)	31.74	22.90	31.38	24.40	27.60
Water		n. d.	m. d.		
Cementation Index	1.68	3.15	1.62	3.60	2.29

* Data insufficient for averaging.

1. Hancock, Md. C. Richardson, analyst. Brickbuilder, vol. 6, p. 151. July, 1897.
2. Cumberland, Md. E. C. Boynton, analyst. Quoted by Gillmore, "Limes, Cements, and Mortars," p. 125.
3. Hancock, Md. C. Huse, analyst. Quoted by Gillmore, "Limes, Cements, and Mortars," p. 125.
4. Cumberland, Md. C. Richardson, analyst. Brickbuilder, vol. 6, p. 151. July, 1897.
5. Average of preceding four analyses.

TABLE 98.

ANALYSES OF NATURAL-CEMENT ROCKS, MANKATO, MINN.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	16.00	12.14	10.10	16.80	8.90	11.80
Alumina (Al_2O_3)	5.85	4.62	2.78	8.76	3.30	3.46
Iron oxide (Fe_2O_3)	2.73	1.84	1.34	tr.	1.02	tr.
Lime (CaO)	22.40	22.66	25.96	22.20	24.85	24.64
Magnesia (MgO)	14.99	16.84	14.91	11.99	18.49	16.61
Alkalies (K_2O,Na_2O)	0.76	3.52	3.50	4.75	1.53	2.59
Sulphur trioxide (SO_3)	n. d.	0.13	0.26	0.22	0.18	0.22
Carbon dioxide (CO_2)	34.11	39.07	41.29	35.90	41.80	40.85
Cementation Index	1.22	0.88	0.69	1.45	0.58	0.77

1. C. F. Sidener, analyst. 11th Ann. Rept. Minn. Geol. Surv., p. 179.
2–6. Clifford Richardson, analyst. Cement Directory, p. 206.

TABLE 99.

ANALYSES OF NATURAL-CEMENT ROCKS, ROSENDALE DISTRICT, N. Y.

	1.	2.	3.	4.	5.	6.	7.	8.
Silica (SiO_2)	10.90	15.37	18.11	18.76	21.32	21.41	23.80	18.52
Alumina (Al_2O_3)	3.40	9.13	4.64	8.34	7.39	10.09	4.17	6.34
Iron oxide (Fe_2O_3)	2.28	2.25	3.00	1.85	1.71		4.71	2.63
Lime (CaO)	29.57	25.50	24.30	25.96	23.75	25.80	22.27	25.31
Magnesia (MgO)	14.04	12.35	14.26	11.07	11.07	10.09	12.09	12.13
Alkalies (K_2O,Na_2O)	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n.d.	n. d.
Sulphur trioxide (SO_3)	0.61	n. d.	tr.	1.35	1.90	0.66	0.90	0.90
Carbon dioxide (CO_2)	37.90	34.20	34.01	32.00	30.74	30.93	31.00	33.31
Water	n. d.	1.20	n. d.	n. d.	n. d.		n. d.	n. d.
Cementation Index	.....	.....	.....	.....	.....	.....	.....	1.43

1. Lawrenceville. J. O. Hargrove, analyst. Letter to writer, Oct. 4, 1900.
2. Rondout. L. C. Beck, analyst. "Mineralogy of N. Y.," p. 78.
3. Lawrenceville. J. O. Hargrove, analyst. Letter to writer, Oct. 4, 1900.
4. " " " " " " Oct. 4, 1900.
5. " " " " " " Oct. 4, 1900.
6. " Rosendale district. C. Richardson, analyst. Brickbuilder, vol. 6, p. 151. July, 1897.
7. Lawrenceville. J. O. Hargrove, analyst. Letter to writer, Oct. 4, 1900.
8. Average of preceding seven analyses.

TABLE 100.

ANALYSES OF NATURAL-CEMENT ROCKS, SCHOHARIE COUNTY, N. Y.

	1.	2.	3.
Silica (SiO_2)	12.89	9.92	11.50
Alumina (Al_2O_3)	11.15	n. d.	
Iron oxide (Fe_2O_3)		n. d.	1.50
Lime (CaO)	30.90	38.26	31.75
Magnesia (MgO)	9.38	9.00	14.91
Carbon dioxide (CO_2)	34.60	39.96	40.34
Cementation Index	1.07		

1. Bottom of cement-bed, Howe's Cave. C. O. Schaeffer, analyst. 18th Ann. Rept. N. Y. State Geologist, p. 69.
2. Top of cement-bed, Howe's Cave. C. O. Schaeffer, analyst. 18th Ann. Rept. N. Y. State Geologist, p. 69.
3. Howe's Cave. L. C. Beck, analyst. "Mineralogy of New York," p. 79.

TABLE 101.

ANALYSES OF NATURAL-CEMENT ROCKS, CENTRAL NEW YORK.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	10.97	10.95	13.50	8.95	11.76	10.66
Alumina (Al_2O_3)	4.46	5.32		4.90	2.73	4.35
Iron oxide (Fe_2O_3)	1.54	1.30	1.25	1.75	1.50	1.47
Lime (CaO)	27.51	30.92	25.24	27.35	25.00	27.20
Magnesia (MgO)	16.90	13.64	18.80	16.70	17.83	16.77
Carbon dioxide (CO_2)	37.94	38.31	39.80	38.65	39.33	38.81
Water	n. d.	n. d.	1.41	1.70	1.50	1.53
Cementation Index	.....	.....	.....	.....	.....	0.71

1. Upper cement-bed, E. B. Alvord quarry, Jamesville, Onondaga County. Bull. 44 N. Y. State Mus., p. 806.
2. Lower cement-bed, E. B. Alvord quarry, Jamesville, Onondaga County. Bull. 44 N. Y. State Mus., p. 806.
3. One and one-half miles west of Manlius, Onondaga County. L. C. Beck, analyst. "Mineralogy of New York," p. 81.
4. One and one-half miles southwest of Chittenango, Madison County. L. C. Beck, analyst. "Mineralogy of New York," p. 80.
5. Chittenango, Madison County. Seybert, analyst. Trans. Am. Philos. Soc., vol. 2, n. s., p. 229.
6. Average of preceding five analyses.

TABLE 102.

ANALYSES OF NATURAL-CEMENT ROCKS, AKRON-BUFFALO DISTRICT, NEW YORK.

	1.	2.	3.	4.
Silica (SiO_2)	9.03	10.68	33.80*	9.85
Alumina (Al_2O_3)	2.25	4.61	3.96	3.10
Iron oxide (Fe_2O_3)	0.85		0.88	0.87
Lime (CaO)	26.84	25.65	19.93	26.25
Magnesia (MgO)	18.37	17.93	9.17	18.15
Alkalies (K_2O,Na_2O)	0.85	n. d.	n. d.	
Sulphur trioxide (SO_3)	n. d.	n. d.	0.50	
Carbon dioxide (CO_2)	40.33	.....	25.90	
Water	0.98	.....		
Cementation Index	.....	.....	.....	0.610

* Called "silica, clay, and insoluble silicates."

1. G. Steiger, analyst. Bulletin 168, U. S. Geol. Survey.
2. Lathbury and Spackman, analysts.
3. E. Boynton, analyst. Gillmore, "Limes, Cements, and Mortars," p. 125.
4. Average of analyses 1 and 2.

TABLE 103.

ANALYSES OF NATURAL-CEMENT ROCKS, NORTH DAKOTA.

	1.	2.	3.	4.	5.
Silica (SiO_2)	14.00	16.60	13.10	16.20	16.54
Alumina (Al_2O_3)	6.70	7.10	7.60	7.56	8.20
Iron oxide (Fe_2O_3)					
Lime (CaO)	37.60	35.50	37.80	35.10	35.20
Sulphur trioxide (SO_3)	0.58	0.60	n. d.	n. d.	n. d.
Sulphur (S)	1.45	1.38	n. d.	n. d.	n. d.
Cementation Index	1.24				

TABLE 104.

ANALYSES OF NATURAL-CEMENT ROCKS, OHIO.

	1.	2.	3.	4.	5.
Silica (SiO_2)	39.95	42.0	16.41	30.60	15.65
Alumina (Al_2O_3)	20.22	7.0	5.44	13.00	6.8
Iron oxide (Fe_2O_3)		7.1	3.38		2.5
Lime (CaO)	10.06	9.91	26.05	22.74	38.64
Magnesia (MgO)	2.92	5.81	12.55	7.23	1.62
Carbon dioxide (CO_2)	24.03	14.18	34.32	25.81	32.14
Water and organic		14.0	n. d.	n. d.	n. d.
Cementation Index	.....	.....	.....	.....	1.25

1. Defiance. J. E. Whitfield, analyst. Bull. U. S. Geol. Survey No. 55, p. 80.
2. Defiance. R. C. Kedzie, analyst. Cement Directory.
3. Bellaire. N. W. Lord, analyst. Repts. Ohio Geol. Surv., vol. 6, p. 673.
4. Warnock. Wormley, analyst. Rept. Ohio Geol. Surv., 1870, p. 451.
5. New Lisbon. N. W. Lord, analyst. Rept. Ohio Geol. Surv., vol. 6, p. 673.

TABLE 105.

ANALYSES OF NATURAL-CEMENT ROCKS, LEHIGH DISTRICT, PA.

	1.	2.	3.	4.
Silica (SiO_2)	11.62	18.34	27.77	19.24
Alumina (Al_2O_3)	6.25	7.49	14.29	9.34
Iron oxide (Fe_2O_3)				
Lime (CaO)	44.20	37.60	29.94	37.25
Magnesia (MgO)	1.27	1.38	1.55	1.40
Carbon dioxide (CO_2)	36.11	31.06	26.30	32.47
Water	n. d.	3.94		
Cementation Index	0.843	1.49	2.87	

1. Siegfried, Pa. Mineral Industry, vol. 1, p. 49.
2. Coplay, Pa. Mineral Industry, vol. 1, p. 49.
3. Lehigh district. Quoted by C. Richardson. Brickbuilder, vol. 6, p. 151. July, 1897.
4. Average of preceding three analyses.

TABLE 106.

ANALYSES OF NATURAL-CEMENT ROCKS, VIRGINIA.

	1.	2.	3.
Silica (SiO_2)	17.38	17.21	17.30
Alumina (Al_2O_3)	7.80	tr.	6.18
Iron oxide (Fe_2O_3)		1.62	1.62
Lime (CaO)	34.23	24.85	29.54
Magnesia (MgO)	9.51	16.58	13.05
Carbon dioxide (CO_2)	30.40	37.95	34.17
Cementation Index	.....	.....	1.18

1. Balcony Falls. E. C. Boynton, analyst. Gillmore, "Limes, Cements, and Mortars," p. 125.
2. Balcony Falls. C. L. Allen, analyst. "The Virginias," vol. 3, p. 88.
3. Average of preceding two analyses.

TABLE 107.

ANALYSES OF NATURAL-CEMENT ROCKS, MILWAUKEE DISTRICT, WIS.

	1.	2.	3.	4.	5.
Silica (SiO_2)	17.00	17.56	17.56	16.99	17.28
Alumina (Al_2O_3)	4.25	1.41	1.40	5.00	3.02
Iron oxide (Fe_2O_3)	1.25	3.03	2.24	1.79	2.21
Lime (CaO)	24.64	25.50	27.14	23.15	25.11
Magnesia (MgO)	11.90	15.45	13.89	16.60	14.46
Carbon dioxide (CO_2)	32.46	37.05	36.45	36.47	n. d.
Cementation Index	.....	.....	.....	.....	1.18

1. Mineral Industry, vol. 6, p. 95.
2. Trans. Am. Inst. Min. Engrs., vol. 8, p. 507.
3. " " " " " vol. 8, p. 507.
4. " " " " " vol. 8, p. 507.
5. Average of preceding four analyses.

European Natural-cement Rocks.

As noted later, the European natural-cement industry dates back to 1796, in which year the manufacture of natural cement was commenced simultaneously in France and England. At present the industry is established in practically every country of Europe, though it is of course subject to severe competition from Portland cement on the one hand and the better class of hydraulic limes on the other. European natural cements form two fairly distinct classes, which are there called respectively " natural Portlands " and " Roman cements."

(1) The **natural Portlands,** which are described on pages 215-216 in detail, are natural cements of low cementation index (1.05 to 1.15 usually), low in magnesia, and burned at fairly high temperatures. In consequence of the combination of their low index and relatively high burning, these products approach true Portland cements in analysis and physical properties, though they necessarily vary considerably from time to time according to the rock from which they are made. The best of these products will pass low-grade Portland tests, and were formerly largely exported to this country, where they were unloaded on the architects and engineers who specified " foreign Portland cement." The poorer " natural Portlands " are often adulterated with slag or unburned limestone, in order to make their bulk composition agree on analysis with that of true Portlands.

While the " natural Portlands " are often useful products, there seems to be no reason for classing them with the true Portlands, for the term Portland is now understood to imply that a very careful and finely ground artificial mixture has been made before burning.

(2) The **Roman cements** form the second class of European natural cements. They are usually cements of moderately high index (1.20 to 1.60), and are also usually but not invariably low in magnesia. They correspond therefore quite closely, so far as index is concerned, to the best of the American natural cements. In American practice, however, low-magnesia natural cements are quite rare, as can be seen by referring to the tables of analyses on pages 244 to 251, while in Europe high-magnesia cements are very scarce.

In France the normal or quick-setting natural cements are called *ciment prompt*; slower-setting products are the *ciments demi-lente*, which at times approach the " natural Portlands " in their characters.

Natural-cement materials of Belgium.—" Natural Portland " cement, as well as Roman cement, is extensively manufactured in certain parts of Belgium.

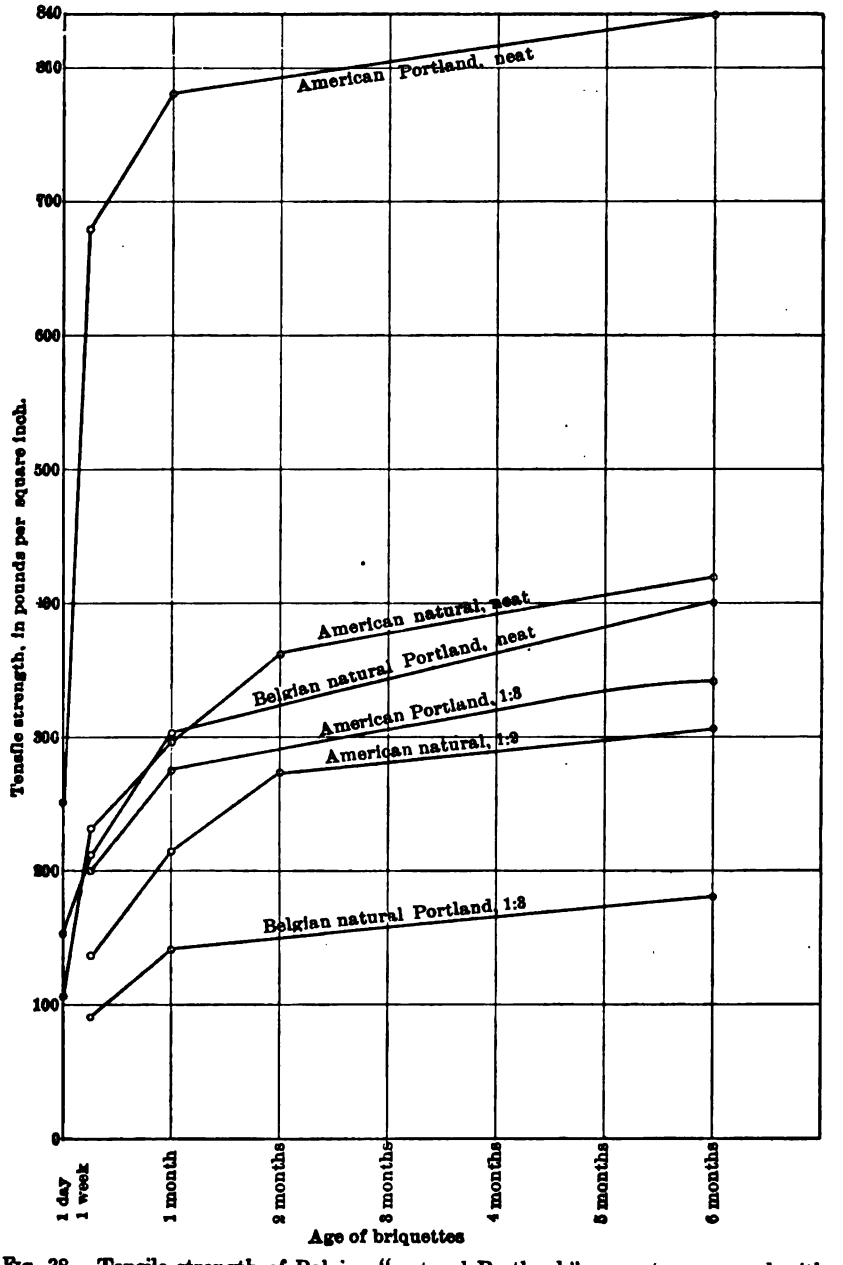

FIG. 38.—Tensile strength of Belgian "natural Portland" cements compared with others.

The following analysis is representative of the composition of the rock from which these " natural Portlands " are made:

Silica (SiO_2)	15.75
Alumina (Al_2O_3)	3.95
Iron oxide (Fe_2O_3)	1.00
Lime (CaO)	43.10
Magnesia (MgO)	0.49
Sulphur trioxide (SO_3)	0.50
Carbon dioxide (CO_2) and Water	35.21
Cementation Index	1.12

It will be seen that if rock of the composition represented by the above analysis could be steadily obtained it would certainly be an excellent natural mixture for a Portland cement. In composition it is admirable, while its index is about that of the average commercial Portland. In practice, however, the variations in composition of the rocks from various parts of the quarry are sufficient to prevent the product from being sufficiently uniform to be considered a Portland cement in our modern use of that term. This will be seen on referring to the analyses of these Belgian products given on page 251.

The chief Belgian production is in the region of Tournai. Here are made true artificial Portlands, " natural Portlands," and ordinary natural or Roman cements.

TABLE 108.

ANALYSES OF NATURAL-CEMENT ROCKS, ENGLAND.

	1.	2.	3.	4.	5.
Silica (SiO_2)	32.00	18.0	17.20	33.00	21.90
Alumina (Al_2O_3)		6.6	6.8		3.50
Iron oxide (Fe_2O_3)		3.7	12.8		8.20
Lime (CaO)	35.28	39.64	29.34	33.88	32.37
Magnesia (MgO)	2.00	0.10	3.33	2.71	2.71
Alkalies (K_2O,Na_2O)	0.80	n. d.	1.00	0.80	1.10
Carbon dioxide	29.92	29.46	26.73	29.61	28.42
Water	n. d.	1.30	2.80	n. d.	1.80

1. Sheppey septaria. Redgrave, "Calcareous Cements," p. 49.
2. Sheppey septaria. Berthier, analyst. Burnell, "Limes, Cements, Mortars, etc.," p. 80.
3. Sheppey septaria. Knauss, analyst. Zwick, "Hydraulischer Kalk und Portland-Cemente," p. 69.
4. Harwich septaria. Redgrave, "Calcareous Cements," p. 49.
5. Harwich septaria. Knauss, analyst. Zwick, "Hydraulischer Kalk und Portland-Cements," p. 69.

Natural-cement materials of England.—The materials used by Parker, the first manufacturer of English natural cements, were septaria —i.e., nodules of clayey lime carbonate. These occur in certain forma-

tions in the south of England, and are still used in the English natural-cement industry. The supply is obtained along the coasts, where the nodules have been washed out of the beds which contain them.

Excavation of the Rock.*

In excavating a natural-cement rock the preferable method of working, so far as cheapness is concerned, is quarrying. But so many of the natural-cement beds now worked are thin (from 4 to 8 feet in total thickness) or occur in such steeply inclined positions, that a surprisingly large percentage of the raw material is obtained by mining. In the Rosendale district of New York, for example, mining is the common mode of extracting the rock; and the same is true of the plants in the Akron district, New York, of those in Maryland, North Dakota, Illinois and Kansas, of the Howard plant in Georgia, and of many of the Louisville district plants. The plants of the Milwaukee district, the Rossville plant in Georgia, a number of those in the Louisville district, and several others work open quarries.

This difference in general practice, taken in connection with differences in labor costs, etc., causes a wide variation between different plants in the total cost of raw material delivered at the kilns.

Open quarries can be readily worked at costs of from 20 to 35 cents per ton of rock. In most cases the question of handling stripping economically is more important than the costs of actual quarrying. At one of the Louisville district plants, where hoists are used in the quarry (Fig. 39) for loading the cars, the stripping is removed by scrapers whose power is derived from these hoists.

In an area such as the Rosendale district, where practically all the cement rock is won by mining, costs will naturally be higher than where open quarries are operated. At one of the largest mills the rock can be delivered on top of the kilns for a trifle under 50 cents per ton. I am informed that at another large mill, rock was mined for a series of years at a cost of about 35 cents per ton.

Summing up these considerations, it is probably within safe limits to say that the cost per ton of rock may vary from about 20 cents in a well-managed quarry to perhaps 60 cents or even more in a mine. As the rock will lose from 25 to 40 per cent of weight during the process of burning (averaging about 33⅓ per cent), the cost per ton of burned

* Further details concerning quarrying costs and methods will be found on pp. 367–381.

rock will vary from 30 to 90 cents. Reducing this to terms of barrels of cement, the cost of raw material per barrel of finished cement may range from 4 to 13 cents.

After the raw material has been excavated, no preliminary treatment is strictly necessary before sending it to the kilns. It is advisable,

FIG. 39.—Loading cars, Speed quarry, Speeds, Ind.

however, to feed the kilns with lumps of approximately equal size, because if the charge consists of a mixture of large and small masses of rock the latter will be overburned before the former are properly calcined. In most plants this rough sizing is accomplished by sledging the larger pieces at the quarry. A few plants, however, use crushers, one installation being illustrated in Fig. 40.

References on natural-cement rock.—The natural-cement rocks of the various states are described more fully in the reports and papers

listed below. For convenience these have been arranged by States in alphabetical order.

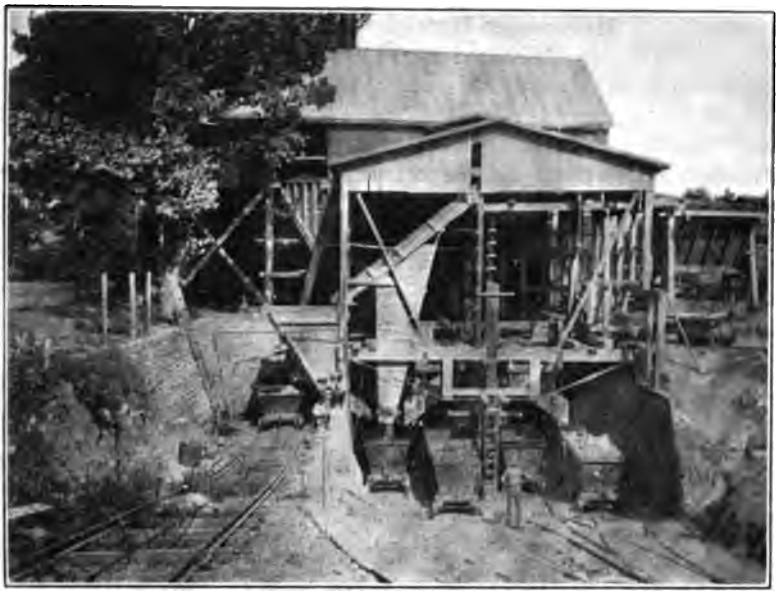

FIG. 40.—Crusher for raw rock at Speed mill, Speeds, Ind

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CHAPTER XVIII.

MANUFACTURE OF NATURAL CEMENTS.

THE manufacture of natural cement is, compared to that of Portland cement, a very simple proposition from a mechanical point of view. Only two general processes are involved—burning and grinding. In the present chapter these processes will be taken up separately, after which a brief statement will be given as to costs of manufacture.

Burning Practice and Theory.

Before taking up such practical questions as types of kiln used, kinds of fuel, relation of fuel consumption to output, etc., it seems advisable to discuss briefly certain more theoretical aspects of the process of burning. On examination, however, it will be found that even these apparently theoretical phases of the subject have a distinct practical bearing.

Chemical changes during burning.—The rock as it is charged into the kiln is a clayey limestone, consisting essentially of lime carbonate and more or less magnesium carbonate, with clayey matter (silica, alumina, and iron oxide). In addition to these essential ingredients it will usually contain a few per cent each of alkalies (soda and potash), sulphur or sulphur trioxide, and water. During calcination certain chemical changes take place in about the following order.

Any mechanically held water is driven off before the rock has reached a temperature of much over 100° C. (212° F.). At about 400° C. magnesium carbonate begins to be dissociated, its carbon dioxide being driven off and the magnesia remaining in its caustic and active form. When mixed with lime carbonate, as in natural-cement rock, it is probable that this dissociation does not take place much below 700° C. When the rock reaches 750° to 800° C. its lime carbonate is dissociated in like manner. At a somewhat higher temperature its clay is decomposed and combination between the alumina and iron oxide and the lime and magnesia commences. This is aided by the presence of alkalies, which here act as fluxes.

It is probable that some natural cements are burned at temperatures not exceeding 900° C., in which case their strength depends largely on the formation of aluminates and ferrites. When, as in most cases, the temperature is carried to 1100°–1300° C., the silica is attacked and lime and magnesia silicates are formed.

Relation of composition to degree of burning.—It may be set down as a general principle that:

The lower the Cementation Index the higher the temperature that must be reached to secure thorough combination.

A cement with an index of 2.00, for example, can be burned at a temperature little, if any, above that of an ordinary lime-kiln (900° C.), while a cement whose index falls below 1.10 will require a temperature almost equal to that (2300° F.) attained in a Portland-cement kiln.

There are therefore distinct economic advantages, so far as fuel consumption is concerned, in making a cement with a high Cementation Index. It must, however, be recollected that *if the burning is properly done, a cement of low index will be stronger than one of high index.*

By far the most satisfactory proposition to handle, from the manufacturer's point of view, is a product whose index falls between 1.20 and 1.60. Such a rock, if properly burned, will give a cement strong enough to compare favorably with the best American or foreign naturals, while, on the other hand, there is no particular danger of making an unsound product. With an index between these limits the burning temperature may vary considerably, one way or the other, without any danger of leaving too much free lime or magnesia in the clinker. With a cement whose index falls below 1.10 this is not true, for the margin of safety is so narrow that the temperature must be kept up to its highest point under penalty of producing unsound cement.

Losses in burning, etc.—If all the rock fed to the kiln were perfectly burned, the loss in burning would correspond directly to the percentage of carbon dioxide (CO_2) plus water present in the raw rock. On this basis one ton (2000 lbs.) of rock would produce the number of barrels (280 lbs.) of cement given in Table 102.

In actual practice, however, a very large additional percentage must be deducted for losses by overburning or underburning. Bad weather and bad management may carry this loss from clinkering or underburning to a point where one-third of the product of the kiln is spoiled. Improved kilns may reduce the loss from these causes to about 10 per cent, and anything between these limits (10 per cent and 33⅓ per cent) may be expected at a natural-cement plant. Under average conditions I should say that 25 per cent would be a safe allowance.

CO_2 + water.	Clinker.	Cement.
Per Cent.	Pounds.	Barrels.
25	1500	5.36
26	1480	5.28
27	1460	5.21
28	1440	5.14
29	1420	5.07
30	1400	5.00
31	1380	4.93
32	1360	4.85
33	1340	4.78
34	1320	4.71
35	1300	4.64
36	1280	4.57
37	1260	4.50
38	1240	4.43
39	1220	4.36
40	1200	4.28

Types of kiln used.—With but few exceptions the kilns used in the American natural-cement industry are of the vertical continuous mixed-feed type.* That is to say, the rock and fuel are fed to the kiln either mixed together or in alternate layers. Kilns of the separate-feed type, in which the fuel does not come in contact with the rock but is burned in a separate furnace, are rarely used in the cement industry. In the lime industry separate-feed kilns are rapidly supplanting the mixed-feed kilns, but the reasons for using them in burning lime do not hold in burning cement. The principal advantage of the separate-feed kiln is that it gives a clean white product unmixed with fuel ashes. This is, of course, a distinct advantage to a lime manufacturer, but it would be of little importance in the cement industry. On the other hand, the mixed-feed kilns are apparently more economical of fuel than the others.

The attention of American natural-cement manufacturers might be profitably turned to consideration of some of the improved types of continuous kilns. The Aalborg kiln, for example, described on pages 103–104, is used in hydraulic-lime manufacture in Europe, and gives remarkably good results as to fuel consumption and quality of product.

The Campbell kiln is not, properly speaking, a new type of kiln, but rather a kiln containing a new type of "pot." In the ordinary lime or natural-cement kiln the pot or lower portion of the kiln is an inverted oval in shape, with one or more draw-chutes or doors at the side. This

* On pp. 100 to 109 will be found descriptions of the various types of kilns used in the lime industry. These descriptions may be referred to as being of interest in the present connection.

results in a certain amount of concentration of the heat, as the draft is localized near the base of the kiln owing to the effects of the draw-openings. The Campbell kiln-pot, instead of being an inverted egg-shaped mass of solid masonry, is an open grating in the form of an inverted cone. In Figs. 42 and 43 the construction details of the kiln are clearly shown. It will be seen in the front elevation that an open space is left all around the pot, between the grating and the supporting walls of the kiln, so that the drawer has free access to all parts of the grating in case of choking or other difficulty. The openings in the grating distribute the air-supply so that the draft is uniform throughout the kiln.

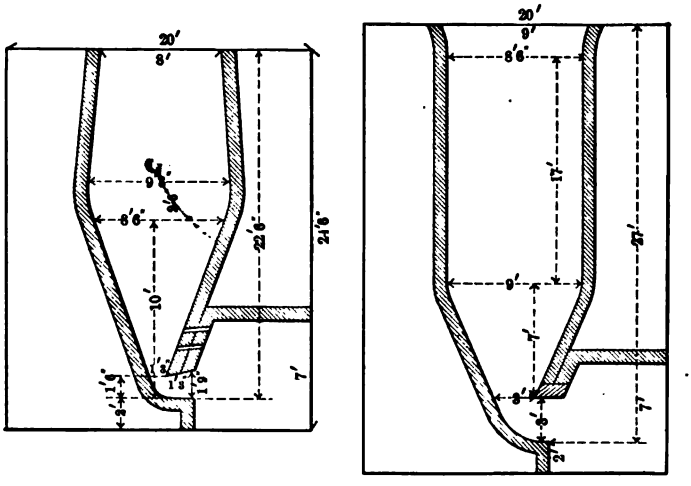


FIG. 41.—Sections of kilns used in natural-cement plants. (After Gillmore.)

It is stated * that the cost of reconstructing the iron-cased kilns of the Milwaukee Cement Company on the Campbell pattern was about $250 per kiln. For a stone kiln the cost of reconstruction would be somewhat higher. A new Campbell kiln, however, would cost somewhat less than a new kiln of ordinary pattern, for the iron "pot" will displace more than its equivalent value of brick and labor.

The Campbell kilns in use at the plant of the Milwaukee Cement Company hold a charge equivalent to about 400 barrels (265 lbs. each) of cement. This is drawn at the rate of 125 to 130 barrels per day, all the drawing for the day being done in ten hours. Nut and slack coal, mixed, are used for fuel. The fuel consumption amounts to about

* Engineering News, Dec. 23, 1897.

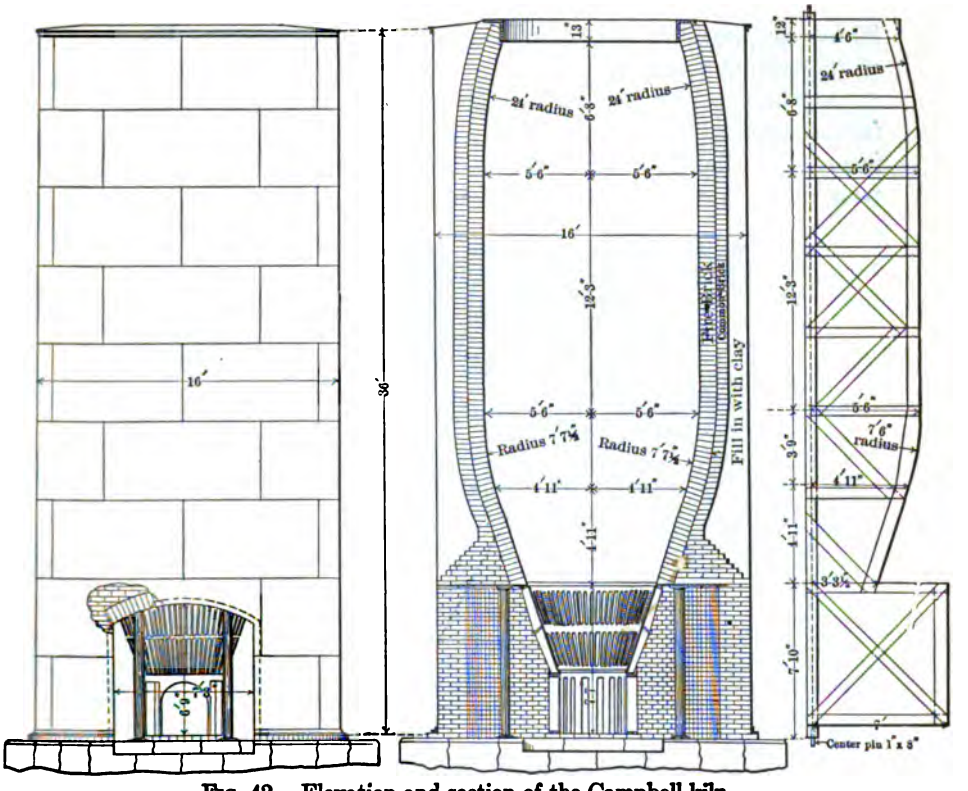


FIG. 42.—Elevation and section of the Campbell kiln.

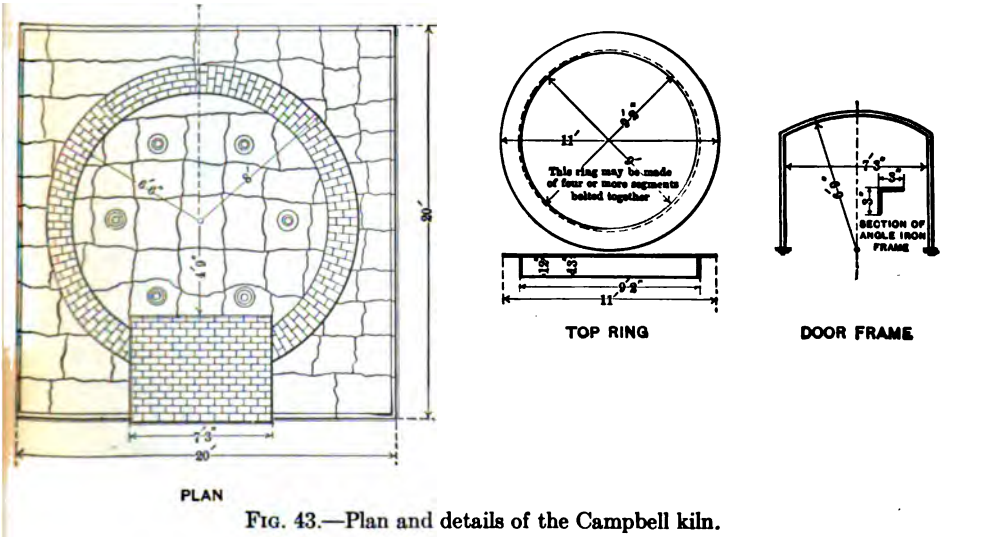


FIG. 43.—Plan and details of the Campbell kiln.

30 lbs. per barrel of cement, equivalent to 11.3 per cent on the weight of the cement produced.

At the Pembina plant in North Dakota a kiln 40 feet high and 10 feet in external diameter is used. The shell is of ½-inch No. 14 boiler iron. The kiln space is broadest at the top, narrows about 6 feet down to a throat about 6 feet in diameter, below which it again enlarges,

FIG. 44.—Kilns of the Lawrence plant, Siegfried, Pa.

reaching almost to the kiln-shell at 15 feet above the base. Below this it is again somewhat contracted to the drawing level. The kiln space is lined with 8-inch fire-brick and the space between these brick and the kiln-shell is filled with ashes. This kiln produces about 50 barrels of 265 lbs. each per day, with a fuel consumption of one ton of Youghiogheny slack. Lignite slack, mixed half and half with Youghiogheny slack, has been used at times, and apparently gives almost as good results as the bituminous slack alone. About 10 per cent of the total product

is underburnt, or clinkered. This record is about equivalent to a fuel consumption of 40 lbs. per barrel, or 15.1 per cent, on the weight of cement produced. This is rather high fuel consumption for natural cement, but, on the other hand, the product is of peculiarly high grade, passing most Portland standards.

The natural-cement kilns at one of the prominent Lehigh district plants are about 30 feet in height and of circular cross-section. Internally they are almost exactly cylindrical, being 10 feet in diameter at the top and 9½ feet in diameter at the base. The cement rock and

FIG. 45.—Kilns and coal-conveyor of the Speed plant, Speeds, Ind.

fuel are fed in alternate layers, the fuel being anthracite coal broken to about ½-inch size. From 35 to 50 lbs. of coal are required to burn one barrel (300 lbs.) of cement, corresponding to a fuel consumption of 11.6 to 16.7 per cent of the weight of cement produced.

Two styles of kiln are in use in the Louisville district. The older and smaller kilns are 36 feet in height, 8 feet in diameter at the top, enlarging to 12 feet at a point 24 feet above the base and again contracting to 4 feet at the base. These are drawn from a chute by use of a swinging gate or apron. Coal and rock are charged in alternate layers. About a week suffices for the passage through the kiln of any

particular mass of material. These small kilns produce about 100 to 125 barrels (265 lbs. each) of cement per day.

The larger kilns are 54 feet from extreme base to top. Viewed from the outside they appear to be cylinders 54 feet high and 16 feet in diameter. Their interior space, however, is 10 feet in diameter at the top, enlarging to 12 feet at a point 18 feet above the base. Below this level, though the interior walls still slope outward, the space is really contracted by the occurrence of a conical mass of brickwork in the center of the kiln. This cone throws the downcoming clinker toward

FIG. 46.—Kilns and kiln-housing, Speed plant, Speeds, Ind.

the draw-gates at the sides. A 9-inch lining of fire-brick is set around the kiln space proper. This is followed by 9 inches of common brick, and the space between the common-brick lining and the exterior kiln shell (which is $\frac{1}{4}$-inch iron) is filled with clay. A kiln of this size and type will produce 150 barrels of cement per day.

The coal used in these kilns is bituminous nut and slack mixed from Pittsburgh or Jellico. About 25.6 lbs. of coal are required to burn a barrel of cement (265 lbs.), equivalent to a fuel consumption of about 9.5 per cent on weight of cement produced.

In the Rosendale district cylindrical kilns are used. These vary

from 8 to 12 feet in diameter and from 20 to 36 feet in height. A kiln fed with one-half ton of anthracite, pea size, will give 75 to 80 barrels of cement per day. This is equivalent to a fuel consumption of about 7 per cent on the weight of cement produced. From one-fifth to one-third of the total produce of the kiln may be overburned clinker or underburned rock. This item, however, depends largely upon the skill of the burners, though it is also affected by uncontrollable factors, such as temperature, weather conditions, force, and direction of the wind, etc.

The kilns in use in the Utica district in Illinois are elliptical in cross-section (plan), with vertical walls. The largest kilns of this type are 30 feet in their longest inside diameter and 12 feet wide. Their total height with foundation is 50 feet, giving a clear height of 45 feet from bottom of draw-hole to top of kiln. These kilns turn out 400 barrels (265 lbs. each) of cement per day, taking 18 to 20 lbs. of coal per barrel of cement. This corresponds to a fuel consumption of only 6.8 to 7.5 per cent.

The second size of Utica kilns is 20 feet by 9 feet in its inside diameters. The smallest size is, like the others, elliptical, with inside diameters of 14 and 7 feet, respectively, and a height of 32 feet from top of bridge wall to top of kiln. These kilns turn out 300 to 375 barrels per day.

All the diameters quoted above are internal measurements. The kiln-shell proper is of $\frac{1}{4}$-inch sheet iron. This is lined, successively, with an 18-inch layer of ashes, 18 inches of stone or common brick, and 9 inches of fire-brick.

The kilns in the central New York district are described * as egg-shaped, 10 feet in diameter at the top, 12 feet at the middle, and $3\frac{1}{2}$ feet at the bottom, with a height of 28 to 42 feet. "There are usually several kilns built together in an embankment of very heavy masonry, so constructed against a hillside that the raw material can be conveniently conveyed there from the quarry and the burned cement easily removed from the bottom of the kiln." The kilns are built of limestone and lined either with sandstone or fire-brick. "When a kiln is ready to be filled a cord of dry, hard, 4-foot wood is put into the bottom and covered 4 inches deep with coarse anthracite coal, then a layer 1 foot thick of cement rock, succeeded by another layer of coal partly coarse and partly fine. This is repeated till the kiln is filled to the top, which required about 10 tons of coal and 15 cords of stone,

* Luther, D. D. The Economic Geology of Onondaga County, New York. 15th Ann. Rept. N. Y. State Geologist, vol. 1, pp. 241–303. 1897.

equal to 1500 bushels of cement. Then the fire is started at the bottom and gradually works its way upward until the whole mass is glowing with heat. After two or three days the gate or door in the bottom is opened and through it the burned cement rock is drawn to the amount of 250 to 300 bushels per day, fresh coal and rock being constantly added to keep the kiln full to the top. One cord of cement rock makes 100 bushels of cement."

Ries states that two types of kilns are in use at the Cummings plant at Akron, Erie County, N. Y. Of seventeen kilns in use there at the time of his visit, eight were of rectangular cross-section, 9 by 22 feet in area, with a height of 34 feet. The remaining nine were circular in cross-section, with a diameter of 9 feet and a height of 34 feet.

Two types of kilns are in use in the Fort Scott district, Kansas. The more common type is cylindrical, 10 to 12 feet in diameter and 30 to 40 feet in total height. The lower 10 feet or so is of stone, on which is set the kiln proper. This is constructed of $\frac{1}{16}$-inch sheet iron, lined with successive layers of coal ashes, clay, common brick and fire-brick. These kilns are drawn daily, and yield 60 to 75 barrels of cement each per day. The fuel used is slack coal, either Arkansas semi-bituminous from Poteau or Huntingdon or a very sulphurous local coal which underlies the cement rock at Fort Scott. The coal is fed with the rock, and is used at the rate of 30 to 35 lbs. per barrel of cement, equal to a fuel consumption of 11.3 to 13.2 per cent on the weight of cement produced. At a three-kiln plant the burning is managed by five men—two feeding and three drawing the kilns.

At one of the Fort Scott plants four flame-kilns are also in use. These have separate fireplaces, so that the fuel and cement do not come into contact. Lump coal must be used for these kilns, and they are said to be more expensive, both in labor and fuel, than the type above described.

The kilns at the plant of the Howard Cement Company, in Georgia, are of the familiar dome type commonly used in lime and natural-cement burning, and are six in number. Four are jacketed with steel and lined with fire-brick, the space between the jacket and the lining being filled with clay. The two remaining kilns differ from these only in the fact that in place of the steel jacket their exterior surfaces are laid up with rock. These rock-jacketed kilns are said to be somewhat more satisfactory than those of the steel-jacketed type.

All the kilns are 25 feet in height and have an output of 60 barrels of cement each. The kilns are charged to the top with fuel and cement

rock, in the proportion of about 300 lbs. of fuel to 2500 lbs. of rock. The fuel used is coal, the sizes being nut, pea, and slack in about equal amounts. Seven or eight days are required, on the average, to "turn a kiln," including charging, burning, and drawing. This corresponds to a fuel consumption of about 18 per cent on the weight of cement produced. In explanation of this high fuel account the reader is referred to the discussion on page 222, where it is shown that the amount of fuel used necessarily increases with the percentage of lime

FIG. 47.—Kilns and loading-tracks, Fort Scott, Kan.

and magnesia. A high-limed cement—and the Howard cement is exceptionally high in lime—therefore requires a very high fuel consumption.

Fuel consumption.—The fuel consumption in natural-cement plants is extremely variable, as is shown by the results tabulated below. The variation is caused in some parts by differences in kiln management and character of fuel, but more largely to differences in the composition of the cement. The cements of lowest index demand calcination at high temperatures, while those of high index may be burned at very low temperature.

TABLE 109.

FUEL CONSUMPTION IN AMERICAN NATURAL-CEMENT PLANTS.

Mill.	Kind of Fuel.	Pounds Fuel per 100 Lbs. Cement.
A	Bituminous nut and slack	9.5
B	Coke	10.0–16.7
C	Bituminous nut and slack	11.3
D	Bituminous slack	11.3–13.2
E	Anthracite nut	11.6–16.7
F	Bituminous slack	15.1
G	Anthracite nut	17.8
H	Bituminous nut, pea and slack	18.0
I	Anthracite pea	7.0
J	Bituminous nut and slack	6.6
K	Anthracite pea and slack	22.0

Hard and soft clinker.—When a natural-cement kiln is drawn, part of the product will consist of hard, clinkered material, part of softer, porous, moderately burned stuff, and part of cores and masses of practically unburned rock. The relative proportions in which these three grades are present will be determined by the type of kiln and the care with which the burning has been conducted. The differences in burning are of course due to some extent to the fact that the masses of rock fed into the kiln differed among themselves in composition; but they are mostly due to the different extent to which the masses have been exposed to the heat of the fuel.

The facts above stated are obvious enough, and the matter might be passed over without further notice if it were not the case that with some rocks the clinkered product will give the best cement, while with other rocks the medium-burned part of the product is the best. This fact certainly requires both consideration and explanation.

The facts themselves are beyond question. In the Rosendale district, for example, from 10 to 20 per cent of the output of the kiln is clinkered material. This clinker is thrown away, for experiments have shown that it does not give a cement nearly as good as the moderately burned product. In the Akron-Buffalo district, on the other hand, the hard, clinkered parts of the product are carefully separated and ground; for experience has shown that these clinkers give a much stronger cement than the softer, more porous masses. These separate facts have been noted by many writers, but no explanation has been offered.

The following seems to explain the difference in practice satisfactorily. It has been noted above that the lower the Cementation

Index the higher the temperature necessary to secure perfect combination of the lime and clay. The Rosendale rock, where the Cementation Index averages around 1.50, will therefore be properly burned at a much lower temperature than the Akron rock, where the index falls below 1.10. But a low temperature means low fuel costs, and so there is not the temptation to economize on fuel in burning a rock of high index that there is in burning one of low index. When rocks of high index are burned, therefore, the temperature and the fuel supply will often be allowed to exceed their proper amount, resulting in the production of clinkered material which has been burned higher than was necessary and is therefore inferior. But in burning a rock of low index, it will be necessary to almost clinker the material before perfect combination is secured. Because of the natural tendency to economize on fuel, the temperature will usually be carried a little lower than is necessary. The result is that in burning rocks of low index the clinkered material is correctly burned and gives the best cement, while the softer masses are really underburned and therefore inferior.

The respective values of the hard and soft parts of the product will therefore depend on the Cementation Index. The following seems a fairly satisfactory statement of the case.

(*a*) When burning a product having an index lower than 1.10, the clinkered portions will furnish the best cement. If separated and ground to proper fineness, they will give a cement approximating to Portland in its physical properties.

(*b*) When burning a product where the index is between 1.10 and 1.25, the clinkered portions and the softer masses will probably be of almost equal value.

(*c*) When burning a product where the index is above 1.25, the clinkered portions may be rejected as worthless; and when the index rises above 1.60, even some of the softer masses may be overburned, unless the temperature be kept sufficiently low.

Seasoning and slaking.—It is obvious that in burning a natural rock in a kiln whose temperature cannot be controlled closely, there are opportunities for great differences between the degree of burning which the rock should have received and the degree which it actually does receive. When the Cementation Index of the product is very high—over 1.60 for example—even a light burning will suffice to decarbonate all of the limestone and to secure combination of the lime with the clayey matter. This is especially true if the silica is comparatively low and the alumina and iron oxide high. A rock of this general type

can therefore vary quite widely in composition and degree of burning without running any risk of turning out an unsound product.

As the percentages of lime and magnesia rise, however, the problem becomes more difficult, and when the index falls below 1.20 a comparatively slight variation in the composition of the rock or in the degree to which it is burned is apt to give a product containing too much free lime for safety.

When this condition—the presence of free lime or magnesia in the product—occurs frequently, the manufacturer has three options. He may (1) burn at a higher temperature, (2) look for a lower-lime rock, or (3) slake the free lime in some way. The first choice would usually be the best, but in nine cases out of ten the manufacturer will take the third, as being apparently the cheapest.

Free lime in a natural cement may be neutralized either by aerating the ground cement or by sprinkling or steaming the unground clinker. When aeration is practiced, the ground cement must be exposed to the air as freely as possible. This implies that it should be spread out, rather than placed in deep bins, and consequently requires considerable floor-space and manual labor. Steaming or sprinkling the unground clinker requires less space and labor, but care must be taken that excess of steam or water is not allowed to reach the cement. The ideal aimed at is to supply sufficient moisture to slake the free lime, but to leave the aluminates and silicates untouched. Simple storage of the clinker, with free access to the air, will often accomplish this result. An incidental benefit to the manufacturer which comes from slaking the clinker (either by steaming, sprinkling, or storage) lies in the fact that the lime in slaking helps to disintegrate the clinker and thus reduce the cost of grinding.

Grinding the Clinker.

When natural cement was first manufactured in this country, the millstones used at flour-mills were the only available fine grinders. Grinding practice at natural-cement plants was therefore soon established in a form which has persisted at many plants to the present day. Quite recently, as Portland cement competition became crushing, some improved methods were adopted.

Until quite recently, grinding practice was almost uniform. The burned rock was sledged if necessary, fed through a cracker or other comparatively coarse reducer, and finished on millstones of one type or another. Within the past few years modern grinding machinery

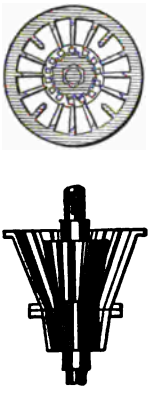


FIG. 48.—Sections of "Cracker" used in natural cement plants. (After Gillmore.)

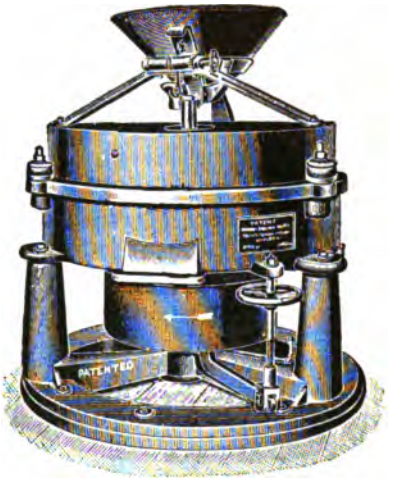


FIG. 49.—Sturtevant rock-emery mill.

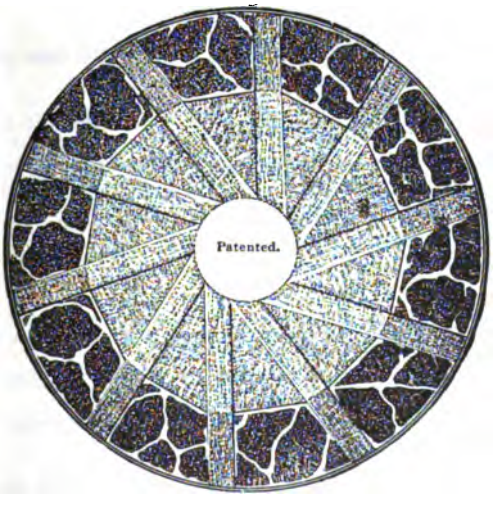


FIG. 50.—Millstone for Sturtevant mill

has been introduced at a few plants and has given such satisfactory results that no natural-cement manufacturer can afford to disregard the innovations.

The gain in strength due to increased fineness of grinding is well shown by the following data, for which I am indebted to the Western Cement Company, of Louisville, Ky. Some time ago this company replaced millstones in one of its best plants by tube mills, and increased the fineness from about 76 per cent through a 100-mesh sieve to about 90 per cent through 100-mesh. With mortar briquettes, 1 cement and 2 sand, this gave the following results:

Fineness through 100-mesh.	7 Days.	28 Days.
76 per cent	63 lbs.	124 lbs.
90 " "	128 "	188 "

Actual mill equipments.—The variations in practice which now exist can best be understood by reference to the following data on the actual equipments of a number of the best American mills:

Mill 1. *a.* 1 Gates crusher.....
b. 2 Lindhard kominuters..... } 1500 bbls. per day
c. 2 Davidsen tube mills.....

Mill 2. *a.* 5 McEntee crackers.....
b. 16-run Esopus millstones..... } 1600 bbls. per day

Mill 3. *a.* 1 coarse pot crusher.....
b. 1 fine pot crusher..... } 200 bbls. per day (run only about one third time)
c. 1 Williams mill.....

Mill 4. *a.* 1 Williams mill.....
b. 1 16-foot Bonnot tube mill.... } 100 bbls. per day

Mill 5. *a.* Sturtevant crushers
b. Cummings grinders
c. 10-run millstones, iron plates
d. 10-run Esopus millstones

Mill 6. *a.* Pot crushers
b. Esopus millstones

Mill 7. *a.* 1 Gates crusher.....
b. 2 dry-pans } 800 bbls. per day
c. 1 Davidsen tube mill.....

Mill 8. *a.* 1 pot crusher.....
b. 1 Williams mill..... } 500 bbls. per day

Mill 9. *a.* Stedman disintegrators
b. Griffin mills

Power required in grinding.—The total horse-power hours required for crushing and grinding a barrel of natural cement will depend on (*a*) the hardness of burning, (*b*) the fineness of the product, and (*c*) the character of the machinery used.

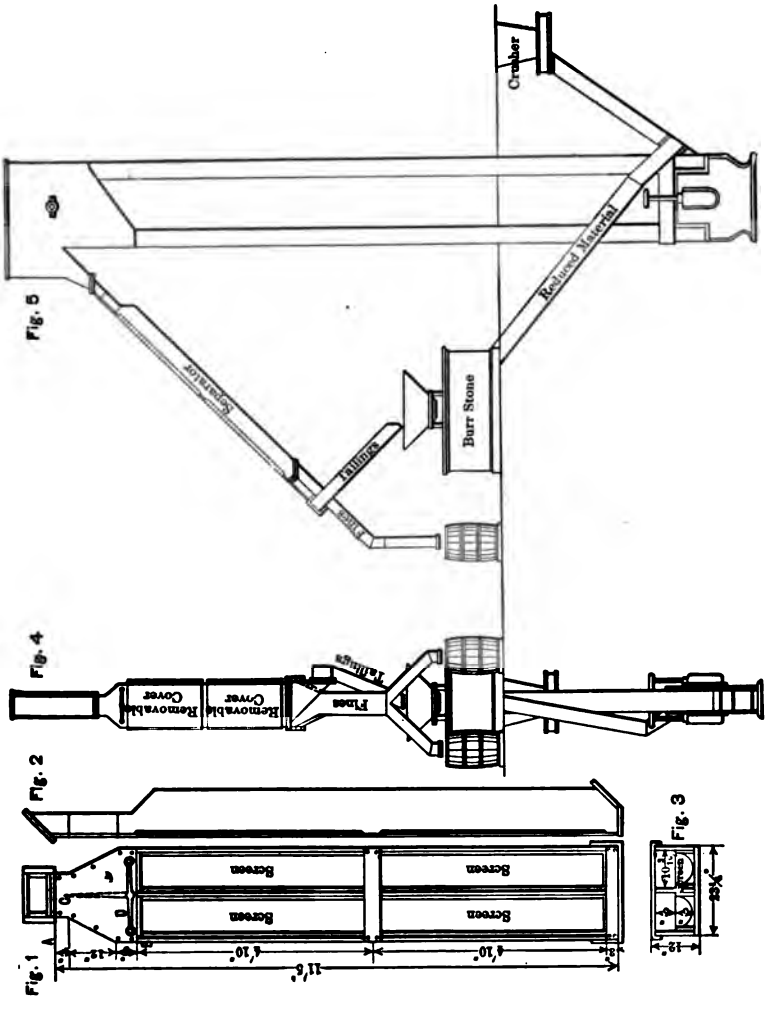


FIG. 51.—Berthelet separating system.

In the table below are given the H.P. hours required to mill a barrel (280 lbs.) of natural cement at eight leading plants. The conditions which affect the power are also briefly noted.

TABLE 110.

POWER REQUIRED IN GRINDING NATURAL CEMENT.

Mill.	H.P. Hours per Barrel (280 Lbs.) Cement.	Burning.	Product.	Milling Machinery.
1	1.5	Fairly hard	Medium	Crushers and millstones *
2	2.3	Medium	Fine	Dry-pan and tube mills
3	2.7	Very light	Fine	Crackers and tube mills
4	2.2	Medium	Fine	Kominuter † and tube mills
5	3.5	Fairly hard	Medium	Crackers and millstones
6	2.9	Medium	Medium	Crusher and Williams mill
7	5.25	Very hard	Very fine	Williams mill and tube mill
8	5.2	Very hard	Fine	Cracker and millstones

* Excellent separating system.
† Not run to full capacity.

Fineness actually attained.—Until quite recently the grinding of an American natural cement was rarely carried further than was necessary to pass 95 per cent of the material through a 50-mesh sieve. There was no particular demand from the engineers for a more finely ground natural cement, and most of the manufacturers merely lived up to the requirements of the average specification. These latter varied considerably, as may be seen from the following table, but in only a few cases was a greater fineness demanded than 85 per cent through a 100-mesh sieve.

The average requirements, then, were low, and the average cement just about passed the requirements. In some cases, however, a higher standard was maintained by the cement manufacturer than by the engineer. The "improved" natural cements of the Lehigh district, most of which are made by mixing Portland and natural cement in various proportions, naturally showed the effect of the very finely ground Portland, and at a few other plants rather fine grinding was practiced.

TABLE 111.

FINENESS REQUIRED BY VARIOUS SPECIFICATIONS.

Specification.	Per Cent Required to Pass.		
	50-mesh.	100-mesh.	200-mesh.
Engineer Corps, U. S. A., 1901	..	80	
New York State Canals, 1896	90	80	
Rapid Transit Subway, New York City, 1900–1901	95	85	
Philadelphia Dept. Public Works, 1893	96		
" " " 1894, 1895	99	85	60
" " " " 1896, 1897	99	90	70

The figures given below represent the results obtained * by very careful sizing of three different brands of natural cements. In making these tests Mr. Bleininger used sieves for the coarser sizing and a washing method for the finer work.

TABLE 112.

FINENESS OF THREE BRANDS NATURAL CEMENT. (BLEININGER.)

No.	Reduced on	Residue on 80-mesh Sieve.	Residue on 120-mesh Sieve.	Residue on 200-mesh Sieve.	Diam. between 0.008 and 0.002 Inch.	Diam. between 0.002 and 0.0002 Inch.	Diam. between 0.0003 and 0.0007 Inch.	Finer than Last Size.	Total Coarser than 200-mesh.
1	Millstones.....	7.36	9.93	3.53	16.42	13.98	14.74	34.04	20.82
2	Tube mill.....	10.53	12.85	8.50	11.39	22.15	20.72	13.85	31.89
3	Millstones.....	12.50	11.59	4.29	16.52	21.95	17.42	15.76	28.37

Packing weights.—In packing natural cements several different standards of weight are in existence in various localities. In the Rosendale, Howe's Cave, and Akron districts the standard barrel weighs about 320 lbs. gross or 300 lbs. net. In the Lehigh district of Pennsylvania the gross and net weights are usually 300 and 280 lbs. respectively. In the Louisville, Utica, Milwaukee, Fort Scott, and other western districts the standard is a barrel weighing about 285 lbs. gross or 265 lbs. net. The recent specifications of the American Society for Testing Materials require packing in bags of 94 lbs., three bags to a barrel.

Exceptions to these general rules occur. The Howard cement of Georgia is naturally so low in specific gravity that an eastern natural-cement barrel will contain only about 240 lbs. of Howard cement. The Pembina cement of North Dakota is, on the other hand, packed at the regular Portland weight of 380 lbs. net per barrel.

Costs of Manufacture.

The items which go to make up the total costs of natural-cement manufacture are (*a*) cost of quarrying for mining the rock, (*b*) cost of labor at kilns and mill, (*c*) cost of fuel for kilns and power, (*d*) interest, etc., on plant. Many of these points have been touched on in the earlier portions of this and the preceding chapter, and will only be summarized briefly below.

Cost of raw material.—The cost of excavating the raw material has been discussed in a preceding chapter (pages 217–218). In the follow-

* Transactions American Ceramic Society, vol. 5, p. 100.

ing estimates the figures there given will be taken as a basis for calculation. It was stated that the cost of raw material, delivered at the kiln, might range from 4 to 13 cents per barrel of finished cement. For our present purposes this range in cost can be decreased somewhat, for at most plants the minimum and maximum limits may be taken as 5 and 10 cents respectively.

Labor costs.—In estimating labor costs it may be accepted for the majority of natural-cement plants that the output will vary between 5 and 10 barrels per day per man employed, counting the men in the mine or quarry as well as those in the mill. As the cost of quarry labor in the present calculation has been already charged against the cost of raw material, the mill force alone should be considered here. Examination of a number of plants proves that the output varies between 12 and 22 barrels per day per man, counting all men employed around the mill and kilns, but excluding quarrymen, miners, and teamsters engaged in hauling rock to the mill.

Fuel costs.—It is probably sufficiently accurate to assume that in the average natural-cement mill the consumption of fuel in the kilns may range from 20 to 65 lbs. coal per barrel of cement. An additional 8 to 20 lbs. of coal will be required to furnish power for grinding and other mill operations. The total coal consumption may therefore vary from 28 to 85 pounds per barrel of cement. In cost coal may easily vary from $1 to $4 per ton, and these figures have been used as the limits in the calculations below.

Total costs per barrel.—Using the above data as a basis, the following estimates of the total costs of manufacture have been prepared.

TABLE 113.

ESTIMATES OF COST OF NATURAL-CEMENT MANUFACTURE.

	Min.	Max.
Rock at mill	$0.05	$0.10
Labor at mill	0.06	0.17
Coal for kilns	0.02	0.12
Coal for power	0.02	0.05
Interest, supplies, etc	0.03	0.06
Total	$0.18	$0.50

Though the minimum quoted may seem surprisingly small, it is very close to the actual costs attained in a prominent district. The above costs do not, of course, include the cost of packing materials, though they do include the labor involved in packing. This distinction has been made because barrels and sacks are usually charged for at a sufficient price to give a small profit on their use.

Through the courtesy of the manager, a typical daily cost report of a large American natural-cement plant is presented in Table 114, below. This mill averages 500 barrels of cement per day, employing 60 men in the quarry, kilns, mill and packing-house. The output per day averaged, therefore, about 8⅓ barrels for each man employed. If quarry labor be excluded, the output per day averaged 20 barrels per day for each man employed in kilns, mill and packing-house. The rate of pay is, however, higher than in most mills, so that the total labor costs are rather high.

TABLE 114.

DAILY COST REPORT OF NATURAL-CEMENT PLANT.

				Cost per Day.	Cost per Bbl.
Quarry...	Labor.....	1 foreman at $3.00....	$3.00	$71.39	$0.143
		2 engineers at $2.00...	4.00		
		2 drillers at $2.00.....	4.00		
		1 blaster at $1.75.....	1.75		
		12 rockmen at $1.75....	21.00		
		15 strippers at $1.75....	26.25		
		1 blacksmith at $2.00..	2.00		
		1 laborer at $1.50.....	1.50		
	Materials..	Explosives.....	5.00		
		Coal.....	2.50		
		Oil.....	0.39		
Kilns....	Labor.....	1 engineer at $2.00....	$2.00	$54.65	$0.109
		2 coalers at $2.00, $1.75.	3.75		
		1 carman at $2.00.....	2.00		
		3 pitmen at $1.75.....	5.25		
		3 loaders at $1.75, $1.50	5.00		
	Materials..	Coal.....	36.00		
		Lights.....	.50		
		Oil.....	.15		
Mill.....	Labor.....	2 engineers at $2.00...	$4.00	$17.70	$0.035
		2 millers at $2.00, $2.25.	4.25		
		1 carman at $1.50.....	1.50		
		1 watchman at $1.50..	1.50		
	Materials..	Coal.....	5.20		
		Lights.....	.50		
		Oil.....	.75		
Packing..	Labor.....	1 foreman at $2.00....	$2.00	$16.00	$0.032
		8 spreaders at $1.75...$14.00			
Total costs, excluding packages.....				$172.74	$0.345

The total cost of cement-manufacture at this plant is therefore close to 34½ cents per barrel. This includes packing labor, but not cost of sacks or barrels, and makes no allowance for interest charges or for sales and general superintendence. Labor costs, as above noted, are

high; and the cement is of low Cementation Index, and therefore requires a very large amount of fuel, averaging about 65 lbs. of coal per barrel.

Production of natural cement, United States.—The natural-cement industry of the United States, commencing in 1819, the new material being used in the Erie Canal construction, grew quite steadily for many years. Its maximum output was reached in 1899, when almost ten million barrels of natural cement were made. But at just that period the American Portland cement industry was commencing its remarkable growth, and within a decade after its year of maximum output American natural cement had fallen off to a very low figure indeed. Statistics covering output over a long series of years are presented in Table 115 following:

TABLE 115.

PRODUCTION OF NATURAL CEMENT, UNITED STATES, 1818–1920.

Period.	Total Barrels.	Period.	Total Barrels.
1818–1830	300,000	1911	926,091
1830–1840	1,000,000	1912	821,231
1840–1850	4,250,000	1913	744,658
1850–1860	11,000,000	1914	751,285
1860–1870	16,420,000	1915	750,863
1870–1880	22,000,000	1916*	842,137
1880–1889	43,463,000	1917*	639,456
1890–1899	80,706,000	1918*	432,966
1900–1909	50,050,000	1919*	528,589
1910–	1,139,239	1920*	615,000

* Including also slag-cement output for the years 1916 and later.

CHAPTER XIX.

COMPOSITION AND PROPERTIES OF NATURAL CEMENTS.

THE preceding chapters will have failed of their purpose if the reader does not now realize that the cements commonly grouped as "natural cements" differ so widely among themselves as to almost prevent *any* general statement being made in regard to the group. These differences have appeared in the composition of the various cement rocks, in the degree of burning to which they were subjected, and in the condition of the mass which resulted from this burning. They will appear still more markedly, however, in the composition and properties of the finished products.

In the present chapter data will be presented bearing on these subjects, but they will be treated as illustrating certain points in connection with the processes of manufacture rather than as guides to the testing or uses of the cements. The chemical composition of the natural cements will first be taken up, after which their physical properties will be noted.

Chemical Composition of Natural Cements.

A large series of analyses of natural cements, both American and foreign, are given in the following tables. For convenience of reference these analyses are given by States arranged in alphabetical order. The Cementation Index has been calculated for a number of these products, and is given in the bottom line of each table.

Georgia.—The two Georgia brands whose analyses are given in Table 116 differ widely in composition and index. The Howard cement is of very low index, much like that from Akron, N. Y., and carries 14 to 20 per cent of magnesia. The Chickamauga cement (Dixie brand) is, on the other hand, of medium high index, and runs very low in magnesia, like the natural cements of the Lehigh district and of France.

Illinois.—The Utica cements are quite close in composition to those from the Rosendale district, N. Y., but run somewhat lower in index.

Indiana–Kentucky.—The Louisville cements are of moderate index and average about 11 per cent magnesia.

TABLE 116.

ANALYSES OF NATURAL CEMENTS, GEORGIA.

	1.	2.	3.
Silica (SiO_2)	22.58	19.60	27.68
Alumina (Al_2O_3)	7.23	11.60	9.10
Iron oxide (Fe_2O_3)	3.35		2.52
Lime (CaO)	48.18	48.86	57.96
Magnesia (MgO)	15.00	18.14	2.52
Cementation Index	1.06	0.895	1.44

1. "Howard." Quoted by Cummings, "American Cements," p. 35.
2. " W. M. Bouron, analyst. Privately communicated.
3. "Dixie." Guild & Co., analysts. Manufacturer's circular.

TABLE 116A.

ANALYSES OF NATURAL CEMENTS, UTICA, ILLINOIS.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	19.89	27.60	34.66	35.43	27.00	29.61
Alumina (Al_2O_3)	11.61	10.60	5.10	9.92	2.76(?)	2.34
Iron oxide (Fe_2O_3)	1.35	0.80	1.00		2.16	1.50
Lime (CaO)	29.51	33.04	30.24	33.67	29.99	29.74
Magnesia (MgO)	20.38	17.26	18.00	20.98	19.79	20.81
Alkalies (K_2O,Na_2O)	5.96	7.42	6.16	.....	1.77	n. d.
Carbon dioxide (CO_2)	n. d.	2.00	4.84	.....	15.96(?)	14.97
Water	n. d.					
Cementation Index	1.19					

1. Haas and McGraw, analysts. Engineering News, April 30, 1896.
2. Quoted by Cummings, "American Cements," p. 36.
3. " " " " " p. 36.
4. J. V. Blaney, analyst. Trans, Am. Inst. Min. Engrs., vol. 13, p. 180.
5. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
6. J. W. Skinner, analyst. Privately communicated.

Kansas.—The natural cements from the Fort Scott district of Kansas are quite close in magnesia percentage and index to those of the Louisville district, as can be seen on comparing the analyses given in Tables 111 and 112.

Maryland.—The Cumberland and Hancock cements are of particularly high index, carrying large percentages of clayey matter and practically no magnesia.

Minnesota.—Both brands of Minnesota cements are high in magnesia and of very low index.

New York.—The cements of the Rosendale district are the typical American natural cements, with rather high index, and carrying 15 to 20 per cent of magnesia.

TABLE 117.

ANALYSES OF NATURAL CEMENTS, LOUISVILLE DISTRICT, IND.–KY.

	1.	2.	3.	4.	5.
Silica (SiO_2)	18.92	21.10	22.54	23.29	24.40
Alumina (Al_2O_3)	11.02	7.50	8.24	5.96	6.20
Iron oxide (Fe_2O_3)	1.91		2.14	2.16	
Lime (CaO)	46.90	44.40	42.31	41.28	41.80
Magnesia (MgO)	0.97†	7.00	5.39	15.39	16.29
Alkalies (K_2O,Na_2O)	n. d.	0.80	2.82	1.98	1.52
Carbon dioxide (CO_2)	n. d.	11.18	n. d.	n. d.	9.89
Water	n. d.	1.16	n. d.	n. d.	
Cementation Index	.....	1.23			

	6.	7.	8.	9.	10.
Silica (SiO_2)	25.28	26.40	23.13	24.76	24.16
Alumina (Al_2O_3)	7.85	6.28	7.87	4.78	4.76
Iron oxide (Fe_2O_3)	1.43	1.00	1.73	3.24	3.40
Lime (CaO)	44.65	45.22	43.79	38.28	46.64
Magnesia (MgO)	9.50	9.00	10.43	11.94	12.00
Alkalies (K_2O,Na_2O)	n. d.	4.00	2.22	n. d.	
Carbon dioxide (CO_2)	7.04	7.86	9.28	10.39	6.75
Water					
Cementation Index	.....	.....	1.28		

† Probably erroneous; omitted in making up average.

1. Quoted by Jameson. "Portland Cement," p. 177.
2. " " Smith. Mineral Industry, vol. 1, p. 50.
3. Haas and McGraw, analysts. Engineering News, April 30, 1896. "Diamond" brand.
4. " " " " " " April 30, 1896. "Star" brand.
5. Lord, analyst. Rept. Ohio Geological Survey, vol. 6, p. 674.
6. Quoted by Cummings. "American Cements," p. 35. "Hulme Star" brand.
7. " " " " " p. 35. "Fern Leaf" brand.
8. Average of preceding seven analyses.
9–10. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.

TABLE 118.

ANALYSES OF NATURAL CEMENTS, FORT SCOTT, KAN.

	1.	2.	3.
Silica (SiO_2)	23.32	21.80	21.67
Alumina (Al_2O_3)	6.99	4.00	10.85
Iron oxide (Fe_2O_3)	5.97	5.00	3.05
Lime (CaO)	53.96	49.80	49.20
Magnesia (MgO)	7.76	12.16	7.90
Carbon dioxide (CO_2)	2.00	4.50	7.27
Water			
Cementation Index	1.19		

1. Quoted by Cummings. "American Cements," p. 35. "Brockett's Double Star" brand.
2. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
3. "Tests of Metals, etc., at Watertown Arsenal," for 1897, p. 403.

TABLE 119.

ANALYSES OF NATURAL CEMENTS, POTOMAC DISTRICT, MD.

(Average index, excluding No. 7, =1.95.)

	1.	2.	3.	4.	5.
Silica (SiO_2)	25.70	28.02	28.30	28.36	28.38
Alumina (Al_2O_3)	12.28	10.20	10.12	9.85	11.71
Iron oxide (Fe_2O_3)	4.22	8.80	4.42	3.07	2.29
Lime (CaO)	52.69	44.48	49.60	45.04	43.97
Magnesia (MgO)	1.44	1.00	3.76	2.82	2.21
Carbon dioxide (CO_2)					
Water					
Cementation Index	1.61	2.09	1.70	1.88	1.99

	6.	7.	8.	9.	10.
Silica (SiO_2)	30.02	36.60	29.74	30.22	29.66
Alumina (Al_2O_3)	13.55	14.58	8.34	8.38	14.76
Iron oxide (Fe_2O_3)	3.00	5.12	4.14	5.38	
Lime (CaO)	44.58	37.50	45.66	39.54	41.96
Magnesia (MgO)	2.76	2.73	2.86	3.80	3.19
Carbon dioxide (CO_2)	.....	.....	8.13	10.20	7.97
Water					
Cementation Index	2.08	2.95	1.92	2.18	2.11

1. Cumberland, Md. A. W. Dow, analyst. Mineral Industry, vol. 6, p. 96.
2. Hancock, Md. Quoted by Cummings. "American Cements," p. 36.
3. Cumberland, Md. A. W. Dow, analyst. Mineral Industry, vol. 6, p. 96.
4. Hancock, Md. A. W. Dow, analyst. Mineral Industry, vol. 6, p. 96.
5. Cumberland, Md. Quoted by Cummings. "American Cements," p. 36.
6. Hancock, Md. A. W. Dow, analyst. Mineral Industry, vol. 6, p. 96.
7. Cumberland, Md. A. W. Dow, analyst. Mineral Industry, vol. 6, p. 96.
8. Hancock, Md. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
9–10. Cumberland, Md. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.

TABLE 120.

ANALYSES OF MINNESOTA NATURAL CEMENTS.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	21.36	28.43	16.24	18.59	19.02	27.70
Alumina (Al_2O_3)	3.34	6.71	5.35	9.14	8.96	7.06
Iron oxide (Fe_2O_3)	3.80	1.94	4.71	1.00	1.24	1.86
Lime (CaO)	45.51	36.31	38.53	40.70	41.18	37.00
Magnesia (MgO)	15.02	23.89	22.73	27.00	26.58	22.63
Alkalies (K_2O,Na_2O)	2.03	1.80	2.30	n. d.	n. d.	n. d.
Sulphur trioxide (SO_3)	1.94	n. d.	n. d.	n. d.	1.27	1.23
Carbon dioxide (CO_2)	10.00	0.92	9.26	3.57	1.75	2.46
Water			0.51		n. d.	n. d.
Cementation Index	0.994	1.20	0.792	0.800	0.816	1.26

1. Mankato. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229. 1897.
2. " Quoted by Cummings, "American Cements," p. 36.
3. " C. F. Sidener, analyst. 11th Ann. Rept. Minnesota Geol. Survey, p. 179.
4. Austin. Quoted by Cummings, "American Cements," p. 36.
5. " Tests of Metals at Watertown Arsenal, 1901.
6. Mankato. Tests of Metals at Watertown Arsenal, 1901.

TABLE 121.

ANALYSES OF NATURAL CEMENTS, ROSENDALE DISTRICT, N. Y.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	25.91	27.98	24.30	27.75	30.84	25.92
Alumina (Al_2O_3)	6.20	7.28	7.22	5.50	7.75	9.40
Iron oxide (Fe_2O_3)	3.81	1.70	5.06	4.28	2.11	
Lime (CaO)	34.62	37.59	33.70	35.61	34.49	33.18
Magnesia (MgO)	20.92	15.00	20.94	21.18	17.77	19.61
Alkalies (K_2O,Na_2O)	n. d.	7.96	n. d.	tr.	4.00	n. d.
Sulphur trioxide (SO_3)	n. d.	n. d.	n. d.	0.5	n. d.	n. d.
Carbon dioxide (CO_2)	5.09	2.49	n. d.	4.05	3.04	4.40
Water	2.80		n. d.	n. d.		
Cementation Index	1.29	.....	.....	1.33		

	7.	8.	9.	10.	11.	12.
Silica (SiO_2)	30.50	30.78	24.42	22.77	29.00	28.91
Alumina (Al_2O_3)	6.84	8.68	8.16	10.43	10.40	10.96
Iron oxide (Fe_2O_3)	2.42		3.96			4.68
Lime (CaO)	34.38	34.14	36.30	34.54	32.35	34.64
Magnesia (MgO)	18.00	19.61	16.93	21.85	19.92	14.82
Alkalies (K_2O,Na_2O)	3.98	1.62	n. d.	3.63	n. d.	1.80
Sulphur trioxide (SO_3)	n. d.	n. d.	n. d.	1.44	n. d.	1.04
Carbon dioxide (CO_2)	3.78	3.57	n. d.	2.84	n. d.	4.50
Water			n. d.	1.59	n. d.	
Cementation Index	.....	.....	.....	.....	.....	1.74

	13.	14.	15.	16.	17.	18.
Silica (SiO_2)	29.84	27.30	21.73	17.17	27.00	29.98
Alumina (Al_2O_3)	15.20	7.14	11.18	10.80	17.50	6.88
Iron oxide (Fe_2O_3)		1.80	4.14			2.50
Lime (CaO)	35.84	35.98	33.77	48.28	35.35	33.23
Magnesia (MgO)	14.02	18.00	21.20	19.13	14.75	17.80
Alkalies (K_2O,Na_2O)	n. d.	6.80	2.99	tr.	n. d.	7.10
Sulphur trioxide (SO_3)	0.93	n. d.	n. d.	1.20	1.41	n. d.
Carbon dioxide (CO_2)	3.73	2.98	n. d.	3.38	4.68	3.13
Water			n. d.	n. d.		
Cementation Index	1.78	1.39	1.19			

	19.	20.	21.	22.	23.
Silica (SiO_2)	31.28	22.75	25.00	28.71	26.66
Alumina (Al_2O_3)	11.30	13.40	8.93	5.88	11.48
Iron oxide (Fe_2O_3)		3.30	2.27	3.60	3.02
Lime (CaO)	36.67	37.60	39.30	27.00	38.33
Magnesia (MgO)	14.35	16.65	16.18	30.00	16.41
Alkalies (K_2O,Na_2O)	n. d.	n. d.	n. d.	n. d.	n. d.
Sulphur trioxide (SO_3)	1.32	n. d.	1.40	1.30	1.35
Carbon dioxide (CO_2)	4.27	5.00	2.66	3.52	2.75
Water		1.36	n. d.	n. d.	n. d.
Cementation Index					

1. "F. O. Norton." Private communication.
2. " " Quoted by Cummings. "American Cements," p. 35.
3. " " Quoted by Lewis. Mineral Industry, vol. 6, p. 96.
4. "Beach's." J. O. Hargrove, analyst. Private communication.
5. "Brooklyn Bridge." Quoted by Cummings. "American Cements," p. 35.
6. " " C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
7. Newark Lime and Cement Co. Quoted by Cummings. "American Cements," p. 35.
8. Newark and Rosendale. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
9. "Old Newark." Booth, Garrett and Blair, analysts. Mineral Industry, vol. 6, p. 96.
10. "Lawrence," Rosendale Cement Co. Mineral Resources, U. S. for 1883–1884.
11. Lawrenceville cement. A. W. Dow, analyst. Mineral Industry, vol. 6, p. 96.
12. "Hoffmann," Lawrence Cement Co. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
13. " " " " " " " vol. 6, p. 229.
14. " " " " Quoted by Cummings. "American Cements," p. 35.
15. " " " " Haas and McGraw, analysts. Engineering News, April 30, 1896.
16. "Hoffmann," Lawrence Cement Co. Mineral Resources U. S. for 1883–1884. Very exceptional analysis.
17. "Rock Lock." C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
18. " " Quoted by Cummings. "American Cements," p. 35.
19. "Hudson River." C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
20. Rondout, N. Y. L. C. Beck, analyst. "Mineralogy of New York," p. 78.
21. "Hoffmann."
22. "Newark and Rosendale." } Tests of Metals, etc., at Watertown Arsenal, 1901.
23. "Norton."

The following analysis is of the natural cement made at Howe's Cave by the Helderberg Portland Cement Company:

ANALYSIS OF NATURAL CEMENT, SCHOHARIE COUNTY, N. Y.

Silica (SiO_2)	26.54
Alumina (Al_2O_3)	5.89
Iron oxide (Fe_2O_3)	
Lime (CaO)	45.30
Magnesia (MgO)	17.06
Cementation Index	1.17

The cements of central New York are of low index, though usually not so low as those of the Akron-Buffalo district.

The natural cements of the Akron-Buffalo district carry usually 20 to 25 per cent magnesia and are of very low index.

TABLE 122.

ANALYSES OF NATURAL CEMENTS, CENTRAL NEW YORK.

	1.	2.	3.	4.
Silica (SiO_2)	20.30	16.56	35.43	24.10
Alumina (Al_2O_3)	13.67	10.77	9.92	11.45
Iron oxide (Fe_2O_3)				
Lime (CaO)	47.48	39.50	33.67	40.22
Magnesia (MgO)	18.55	22.27	20.98	20.60
Cementation Index	.....	.....	.....	1.13

1. Brown Cement Co., Manlius, Onondaga County. W. M. Smith, analyst. 20th Ann. Rept. U. S. Geol. Survey, pt. 6, p. 428.
2. Near Chittenango, Madison County. L. C. Beck, anlayst. "Mineralogy of New York," p. 80.
3. South of Utica, Oneida County. Gillmore. "Limes, Cements, and Mortars," p. 125.
4. Average of preceding three analyses.

TABLE 123.

ANALYSES OF NATURAL CEMENTS, AKRON-BUFFALO DISTRICT, N. Y.

	1.	2.	3.	4.	5.
Silica (SiO_2)	17.14	22.62	20.20	22.70	16.48
Alumina (Al_2O_3)	7.61	7.44	4.40	7.40	4.40
Iron oxide (Fe_2O_3)	2.00	1.40	2.80	.....	2.00
Lime (CaO)	36.83	40.68	41.60	36.31	39.20
Magnesia (MgO)	25.09	22.00	22.24	25.72	26.52
Alkalies (K_2O,Na_2O)	3.64	2.23	1.62	n. d.	1.85
Sulphur trioxide (SO_3)	n. d.	n. d.	2.06	n. d.	1.39
Carbon dioxide (CO_2)	n. d.	3.63	6.90	4.00	6.80
Water	n. d.	n. d.		n. d.	
Cementation Index	0.801	0.874	0.871	0.991	0.686

	6.	7.	8.	9.	10.
Silica (SiO_2)	26.69	20.75	22.94	20.40	23.70
Alumina (Al_2O_3)	7.21	10.02	6.30	6.22	16.70
Iron oxide (Fe_2O_3)	1.30		2.90	2.56	3.30
Lime (CaO)	43.12	37.54	43.74	40.64	37.00
Magnesia (MgO)	19.55	26.14	20.72	25.80	15.30
Alkalies (K_2O,Na_2O)	1.13	2.12	n. d.	n. d.	n. d.
Sulphur trioxide (SO_3)	n. d.	n. d.	n. d.	2.91	1.98
Carbon dioxide (CO_2)	1.00	4.58	1.00	1.47	2.00
Water	n. d.		n. d.	n. d.	n. d.
Cementation Index	1.18	0.932	1.006	0.856	2.21

Average index, excluding No. 10 ..... = 0.911

Average CaO ..... = 39.666

Average MgO ..... = 22.908 = 1.73

1. "Union Akron." Haas and McGraw, analysts. Engineering News, April 30, 1896.
2. "Newman Akron." Quoted by Cummings. "American Cements," p. 35.
3. "Akron Star." C. Richardson, analyst. Brickbuilder, vol. 6, p. 229. 1897.
4. "Buffalo Portland." N. Lord, analyst. Reports Ohio Geological Survey, vol. 6, p. 674.
5. "Buffalo." C. Richardson, analyst. Brickbuilder, vol. 6, p. 229. 1897.
6. "Obelisk." Quoted by Cummings. "American Cements," p. 35.
7. " C. Richardson, analyst. Brickbuilder, vol. 6, p. 229. 1897.
8. "Storm King Portland." Tests of Metals, etc., at Watertown Arsenal, 1901.
9. "Akron Star." Tests of Metals, etc., at Watertown Arsenal, 1901.
10. "Obelisk." Tests of Metals, etc., at Watertown Arsenal, 1901.

North Dakota.—The Pembina cement is a highly satisfactory product, of high index and low magnesia, much like the Chickamauga cement of Georgia.

Pennsylvania.—The Lehigh district natural cements are low in magnesia. As marketed they are often very badly mixed products. Portland cement is usually added, while adulteration with coke and ground limestone is not unknown.

West Virginia–Maryland.—These cements are fairly low in magnesia and usually of very high index.

TABLE 124.

ANALYSES OF NATURAL CEMENT, NORTH DAKOTA.

	1.	2.	3.	4.
Silica (SiO_2)	24.62	23.60	23.90	24.72
Alumina (Al_2O_3)	15.12	16.50	15.90	15.00
Iron oxide (Fe_2O_3)				
Lime (CaO)	52.30	51.40	51.40	51.30
Cementation Index	1.61			

	5.	6.	7.	8.
Silica (SiO_2)	24.40	24.40	24.06	24.46
Alumina (Al_2O_3)	15.26	15.38	15.00	15.30
Iron oxide (Fe_2O_3)				
Lime (CaO)	52.07	51.96	51.96	52.37
Cementation Index	.....	.....	1.58	

1–8. Analyses of natural cement, Pembina Cement Co., Milton, N. D.

TABLE 125.

ANALYSES OF NATURAL CEMENTS, LEHIGH DISTRICT, PA.

	1.	2.	3.
Silica (SiO_2)	18.18	18.28	30.40
Alumina (Al_2O_3)	9.78	7.43	10.36
Iron oxide (Fe_2O_3)			2.60
Lime (CaO)	69.18	51.53	52.12
Magnesia (MgO)	1.98	2.07	0.21
Alkalies (K_2O,Na_2O)	n. d.	1.50	n. d.
Sulphur trioxide (SO_3)	n. d.	n. d.	1.24
Carbon dioxide (CO_2)	n. d.	16.26	3.07
Water	n. d.		n. d.

1. Quoted by Smith. Mineral Industry, vol. 1, p. 50.
2. " " " " " vol. 1, p. 50.
3. "Bonneville Improved." Tests of Metals at Watertown Arsenal, 1901.

TABLE 126.

ANALYSES OF NATURAL CEMENTS, SHEPHERDSTOWN-ANTIETAM DISTRICT, W. VA.-MD.

	1.	2.	3.
Silica (SiO_2)	33.42	36.51	33.50
Alumina (Al_2O_3)	10.04	9.36	10.44
Iron oxide (Fe_2O_3)	6.00		3.25
Lime (CaO)	32.79	34.83	29.38
Magnesia (MgO)	9.59	11.33	13.37
Alkalies (K_2O,Na_2O)	0.50	1.25	n. d.
Sulphur trioxide (SO_3)	n. d.	1.49	1.15
Carbon dioxide (CO_2)	7.66	5.13	7.15
Water			
Cementation Index	2.35	2.20	2.23

1. Shepherdstown, W. Va. Quoted by Cummings, "American Cements," p. 35.
2. Shepherdstown, W. Va. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.
3. Antietam, Md. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.

Wisconsin.—The Milwaukee cements are of quite low index, ranging from 1.10 to 1.20, and carry a little more magnesia than do the Rosendale products.

TABLE 127.

ANALYSES OF NATURAL CEMENTS, MILWAUKEE DISTRICT, WIS.

	1.	2.
Silica (SiO_2)	23.16	25.00
Alumina (Al_2O_3)	6.33	4.00
Iron oxide (Fe_2O_3)	1.71	2.80
Lime (CaO)	36.08	33.40
Magnesia (MgO)	20.38	22.60
Alkalies (K_2O,Na_2O)	5.27	2.51
Sulphur trioxide (SO_3)	n. d.	2.59
Carbon dioxide (CO_2) and Water	7.07	9.50
Cementation Index	1.09	1.17

1. Quoted by Cummings. "American Cements," p. 35.
2. C. Richardson, analyst. Brickbuilder, vol. 6, p. 229.

Belgium.—The manufacture and character of the Belgian natural cements have been described in detail on preceding pages. As marketed they are usually cements of low index (1.05 to 1.15) and carry small percentages of magnesia.

England.—English natural cements are commonly products of high index, carrying much clayey matter, and often containing remarkably high percentages of iron oxide.

France.—The analyses given in Table 130 represent a peculiarly homogeneous group of natural cements, a fact which is brought out clearly when their Cementation Indexes are calculated and compared.

TABLE 128.

ANALYSES OF "NATURAL PORTLAND" CEMENTS, BELGIUM.

	1.	2.
Silica (SiO_2)	22.17	28.0
Alumina (Al_2O_3)	4.60	3.0
Iron oxide (Fe_2O_3)	1.23	2.0
Lime (CaO)	60.86	62.0
Magnesia (MgO)	0.73	0.6
Sulphur trioxide (SO_3)	n. d.	1.2
Carbon dioxide (CO_2)	1.46	1.2
Water	0.48	n. d.
Cementation Index	1.09	1.32

1. Compagnie Générale des Ciments Portlands de l'Escaut, Tournai.
2. Dumon et Cie, Tournai.

TABLE 129.

ANALYSES OF NATURAL CEMENTS, ENGLAND.

	1.	2.	3.	4.
Silica (SiO_2)	24.41	31.36	26.12	25.27
Alumina (Al_2O_3)	9.65	5.01	7.92	7.47
Iron oxide (Fe_2O_3)	18.86	11.74	6.46	9.05
Lime (CaO)	41.36	46.36	56.44	55.65
Magnesia (MgO)	4.73	3.93	1.60	1.59
Cementation Index	1.92	.....	.....	1.48

1. Sheppey. Quoted by Redgrave. "Calcareous Cements," p. 49.
2. Harwich. " " " " p. 49.
3. Whitby. " " Zwick, p. 74.
4. London. " " " p. 74.

Germany–Austria.—Analyses of a number of German and Austrian natural cements are given in Table 131. This series includes two interesting analyses (Nos. 5 and 6) of cements of very low index, carrying high percentages of magnesia.

TABLE 130.

ANALYSES OF NATURAL CEMENTS, FRANCE.

	1.	2.	3.	4.
Silica (SiO_2)	24.94	20.50	21.2	21.82
Alumina (Al_2O_3)	9.00	8.40	6.9	8.88
Iron oxide (Fe_2O_3)	1.16	5.70	13.7	12.47
Lime (CaO)	63.64	52.05	56.6	55.69
Magnesia (MgO)	1.26	0.95	1.1	1.12
Sulphur trioxide (SO_3)	n. d.	2.80	n. d.	n. d.
Cementation Index	1.22	1.32	1.32	1.39

	5.	6.	7.	8.
Silica (SiO_2)	23.50	24.25	22.10	22.61
Alumina (Al_2O_3)	12.50	10.00	18.21	19.79
Iron oxide (Fe_2O_3)	3.00	4.00	tr.	tr.
Lime (CaO)	52.50	53.50	55.98	51.63
Magnesia (MgO)	2.50	2.50	0.37	0.37
Sulphur trioxide (SO_3)	1.00	2.00	3.34*	5.60*
Cementation Index	1.46	1.52	1.45	1.63

* Lime sulphate, $CaSO_4$.

1. Vassy. Quoted by Cummings. "American Cements," p. 35. Exceptionally high-limed.
2. " " " Bonnami. "Chaux Hydrauliques," etc., p. 54.
3. " " " Zwick. "Hydraulischer Kalk und Portland-Cement," p. 91.
4. " " " " " " " " p. 91.
5. Valbonnais. Slow-setting. Bonnami. "Chaux Hydrauliques," etc., p. 54.
6. " Very slow. " " " " p. 54.
7. Porte de France. Quick-setting. Bonnami. "Chaux Hydrauliques," etc., p. 151.
8. " " " Slow-setting. " " " " p. 151.

TABLE 131.

ANALYSES OF NATURAL CEMENTS, GERMANY AND AUSTRIA.

	1.	2.	3.	4.	5.
Silica (SiO_2)	28.83	27.88	24.12	23.66	20.80
Alumina (Al_2O_3)	6.40	6.19	6.47	7.24	5.80
Iron oxide (Fe_2O_3)	4.80	4.64	5.28	7.97	1.50
Lime (CaO)	58.38	56.45	59.10	58.88	47.83
Magnesia (MgO)	5.00	4.84	4.98	2.25	24.26
Cementation Index	.....	.....	.....	.....	0.80

	6.	7.	8.	9.	10.
Silica (SiO_2)	22.14	25.00	21.48	26.80	23.67
Alumina (Al_2O_3)	5.75	9.00	6.45	10.30	8.83
Iron oxide (Fe_2O_3)	3.07	4.39	2.80	1.90	5.92
Lime (CaO)	44.22	58.02	56.73	59.80	58.80
Magnesia (MgO)	17.77	1.08	3.04	0.30	0.73
Alkalies (K_2O,Na_2O)	4.72	0.62	.....	0.70	1.22
Cementation Index	1.02	1.39	.....	1.455	1.34

1. Rudersdorf. Michaelis, analyst. Quoted in Wagner's "Chemical Technology," 13th ed., p. 669.
2. Rudersdorf. Quoted by Cummings. "American Cements," p. 35.
3. " " " Zwick. "Hydraulischer Kalk und Portland-Cement," p. 74.
4. Hausbergen. } Michaelis, analyst. Quoted in Wagner's "Chemical Technology," 13th ed.,
5. Tarnowitz. } p. 669.
6. Heidelberg. }
7. Piesting. } Quoted by Zwick. "Hydraulischer Kalk und Portland-Cement," p. 74.
8. Haring. }
9. Kusstein. }
10. Perlmoos. } Quoted by Schoch. "Mörtel-Materialen," p. 74.

Weight and specific gravity.—The specific gravity of American natural cements appears to be greatly underestimated by most engineering authorities. In a recent report, for example, it is stated that "natural cement has a specific gravity of 2.5 to 2.8." In reality very few of our American cements ever fall as low in specific gravity as 2.8, and it would be nearer the truth to say that, as a class, the natural cements range between 2.8 and 3.2.

In the following table (132) a number of careful determinations are given, selected from various sources so as to cover as many cement districts and brands as possible.

Rapidity of set.—Natural cements are normally much quicker-setting than Portlands, but this rapidity of set may be changed by aeration, the use of plaster, etc., to a very remarkable degree.

TABLE 132.

SPECIFIC GRAVITY OF AMERICAN NATURAL CEMENTS.

State.	Locality.	Brand.	Authority.	Specific Gravity
Illinois	Utica.....	?	C. Richardson	2.70
Kansas	Fort Scott...	?	"	2.79
Maryland	Cumberland	Cumberland Hydraulic Cement Mfg. Co.	Phila. Cement Tests, 1897	2.90
"	"	Cumberland Hydraulic Cement Mfg. Co.	" " " 1899	2.846
"	"	Cumberland and Potomac Cement Co.	" " " 1899	2.828
"	"	Potomac	Watertown Arsenal, 1901	2.94
"	Round Top.	?	C. Richardson	2.84
"	" "	?	Phila. Cement Tests, 1899	2.922
Minnesota	Austin....	.....	Watertown Arsenal, 1901	3.15
"	Mankato..	.....	" " 1901	2.93
"	" ..	.....	C. Richardson	2.81
New York	Rosendale.	?	"	3.04
" "	"	Hoffmann	Watertown Arsenal, 1901	3.06
" "	"	Norton	" " 1901	3.03
" "	"	Newark and Rosendale	" " 1901	3.06
" "	Akron....	"Storm King Portland"	" " 1901	3.07
" "	"	Obelisk	" " 1901	3.12
" "	"	Star	Phila. Cement Tests, 1897	3.17
Pennsylvania	Lehigh	Coplay improved	" " " 1897	3.00
"	"	" "	" " " 1899	2.96
"	"	Hercules improved	" " " 1897	2.97
"	"	American improved	" " " 1897	3.07
"	"	" "	" " " 1899	3.02
"	"	Bonneville improved	Watertown Arsenal, 1901	2.85

In 1894–95 Sabin tested the effect of aeration on the setting time of natural cement, with the following results:*

TABLE 133.

EFFECT OF AERATION ON SETTING TIME OF NATURAL CEMENT. (SABIN.)

No.	Direct from Package.		After 19 Days' Aeration.	
	Initial Set, Minutes.	Final Set, Minutes.	Initial Set, Minutes.	Final Set, Minutes.
1.....	52	110	54	173
2.....	50	100	51	164
3.....	44	100	48	166
4.....	60	280	100	326
5.....	101	349	147	306
6.....	87	1200	130	1241
7.....	80	1178	122	1233
8.....	72	1202	125	1227
9.....	108	1256	202	1221
10.....	192	1247	234	1216

* Report Chief of Engineers, U. S. A., 1895, p. 2937.

Effects of gypsum or plaster on natural cements.—Natural cements are affected by the addition of gypsum in regard to setting time and strength in much the same manner as Portland cement would be. The degree to which these effects are produced, for the same percentage of gypsum, depends entirely upon the chemical composition of the respective cements. This fact seems to have been entirely overlooked by experimenters, and in consequence the tests which have been made are deprived of much of their value, because the analysis of the cement is rarely included in the report of the test.

Experiments on the effect of gypsum on the rate of set have been carried out by Sabin,* and the results are embodied in Table 134, below, and are shown diagrammatically in Fig. 52.

TABLE 134.

EFFECT OF PLASTER ON SETTING TIME OF NATURAL CEMENT. (SABIN.)

Brand.	Per Cent Plaster.	Setting Time.	
		Initial, Minutes.	Final, Minutes.
A.....	0	38	543
".....	1	106	414
".....	2	107	527
".....	3	86	671
".....	6	42	632
B.....	0	93	193
".....	1	179	439
".....	2	302	592
".....	3	295	725
".....	6	93	698

From this table it will be seen that the maximum retardation of the initial set took place with both brands when 2 per cent of plaster was used. The final set, however, experienced its greatest retardation in both cases when 3 per cent of plaster was employed.

Sabin also tested † the effects of plaster on the tensile strength of both neat and mortar briquettes. The results of these tests are shown in the following table (135):

These tests would appear to show that the addition of even 1 per cent of plaster has injurious effects on the soundness of the cement, and less markedly on its tensile strength. Unfortunately, the analysis

* Report Chief of Engineers, U. S. A., 1895, p. 2938.

† Report Chief of Engineers, U. S. A., 1896, p. 2857.

of the cement tested is not given, and even its name is suppressed, so that the results are less instructive than they might have been.

TABLE 135.

EFFECT OF PLASTER ON TENSILE STRENGTH OF NATURAL CEMENT. (SABIN.)

Composition.		Per Cent Plaster.	Tensile Strength, Pounds.		
Cement.	Sand.		7 Days.	6 Months.	1 Year.
1	0	0	146	383	
1	0	1	156	398 [1]	
1	0	2	115 [1]	323	
1	0	3	...	312 [2]	
1	0	6	...	234 [3]	
1	2	0	62	374	448
1	2	1	80	312	395
1	2	2	94	355	408
1	2	3	...	86 [3]	131 [3]
1	2	6	...	151 [3]	107 [3]

[1] Surface cracks. [2] Swelled and nearly disintegrated. [3] Badly cracked and swelled.

In general it may be said that the effects of gypsum or plaster will be directly proportional to the percentage of alumina contained in

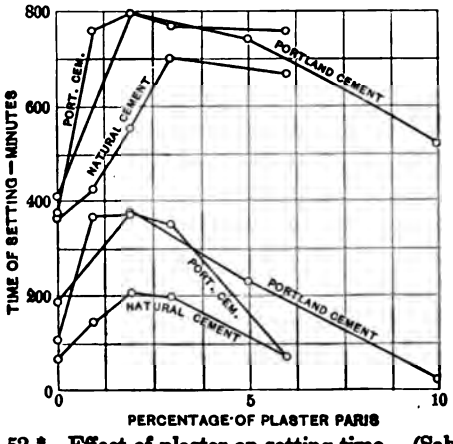


FIG. 52.*—Effect of plaster on setting time. (Sabin.)

the cement. This statement has never before been explicitly made, but it is a necessary corollary from recent studies on the behavior of cements with gypsum and in sea-water.

* From Johnson's "Materials of Construction," p. 187.

Effect of salt on strength.—In laying masonry in freezing weather it has been customary to specify the use of salt in the water used for the mortar. This lowers the freezing temperature of the water, but does

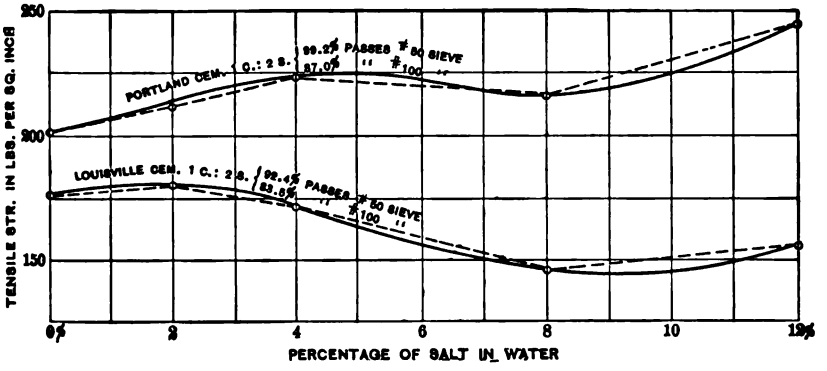


FIG. 53.*—Effect of salt on tensile strength.

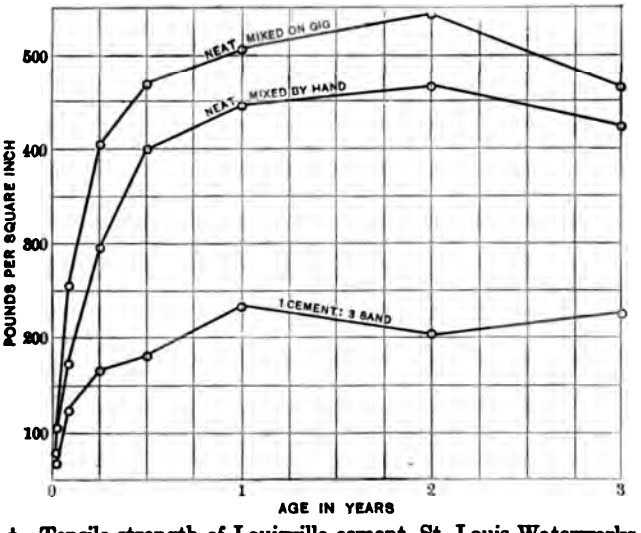


FIG. 54.†—Tensile strength of Louisville cement, St. Louis Waterworks, 1896.

not seem to be of any particular benefit in other respects. It decreases quite markedly the tensile and compresssive strength of the mortars, even when only a small percentage of salt is added.

* From Johnson's "Materials of Construction," p. 618.

† From Johnson's "Materials of Construction," p. 570.

The effect of salt on the strength of natural-cement mortars is shown in Fig. 53. These experiments were made on Louisville and Portland-cement mortars and all tested at six months.

Tensile strength.—In tensile strength the average natural-cement ranks considerably lower than the average Portland. This is particularly noticeable when the cements are tested with sand.

This general rule as to the relative strength of natural and Portland cements is well known, but the exceptions to the rule are not fre-

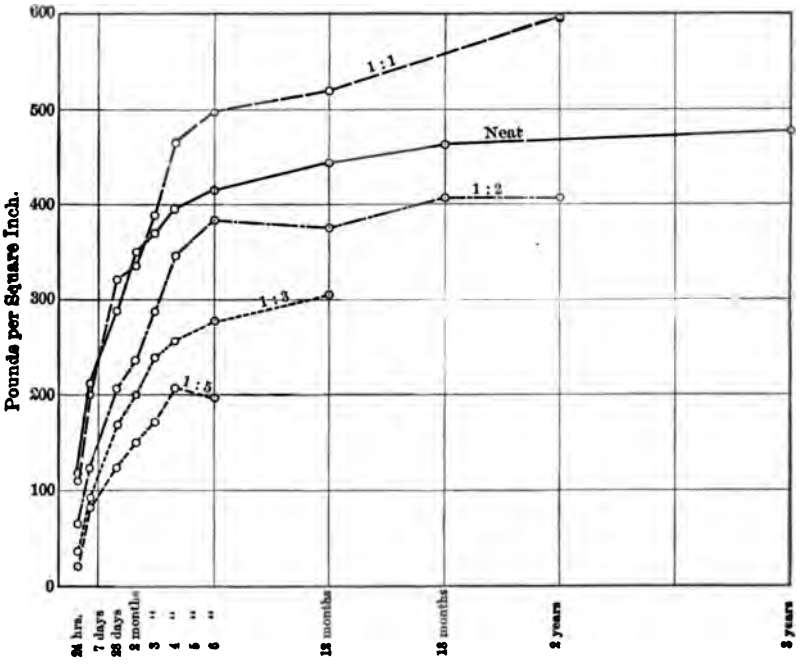


FIG. 55.—Tensile strength of Lehigh district natural cements. (Philadelphia tests, 1893, 1894, 1895, 1896.)

quently discussed. It is a fact, however, that certain brands of natural cements are about as strong, either neat or with sand, as the average imported Portland, and there is no reason why a number of natural cements could not be carried up to this grade. The average results of extensive series of tests on various natural cements are given diagrammatically in Figs. 54–62.

In Fig. 55 are shown the results of a very large number of tensile tests, at various ages up to 3 years, on the " improved " natural cements of the Lehigh district of Pennsylvania.

The results of a number of tests of natural cements from the Cumberland-Hancock district of Maryland have been averaged and are shown diagrammatically in Fig. 56.

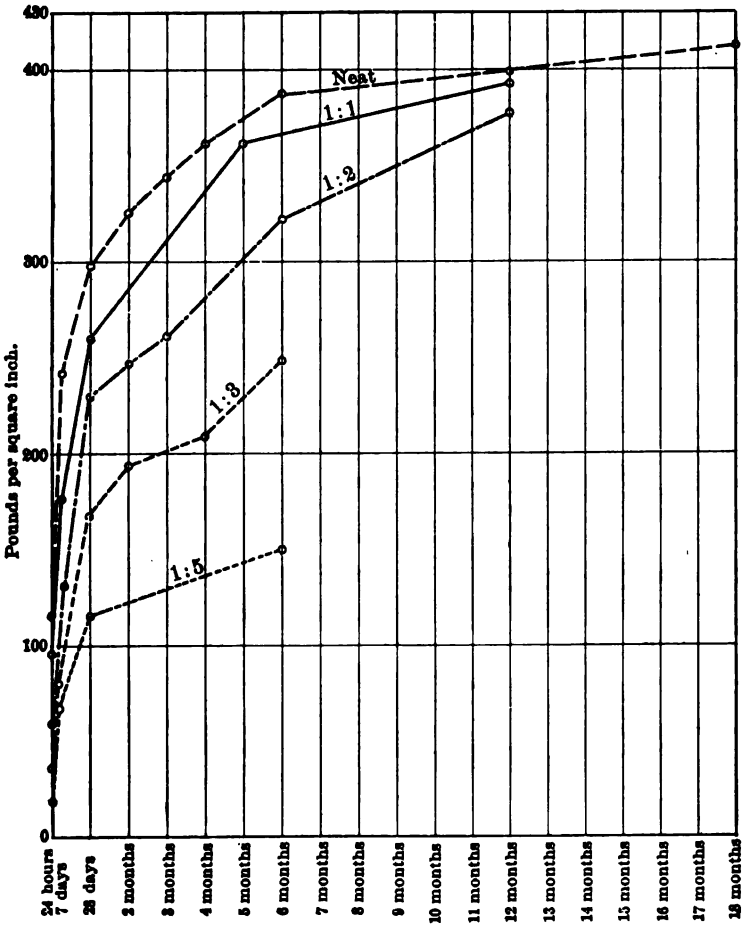


FIG. 56.—Tensile strength of Cumberland natural cements. (Philadelphia tests, 1894, 1895, 1896.)

Tests of natural cements from Akron, N. Y., and Cumberland, Md., during 1897 and 1898, are shown diagrammatically in Fig. 57. These tests cover ages of 1 day to 6 months.

The effect on the tensile strength of varying the proportion of sand is well shown in the tests made by Sabin * and summarized in Table 136. These tests are shown diagrammatically in Fig. 61.

* Report Chief of Engineers, U. S. A., 1895, p. 2982.

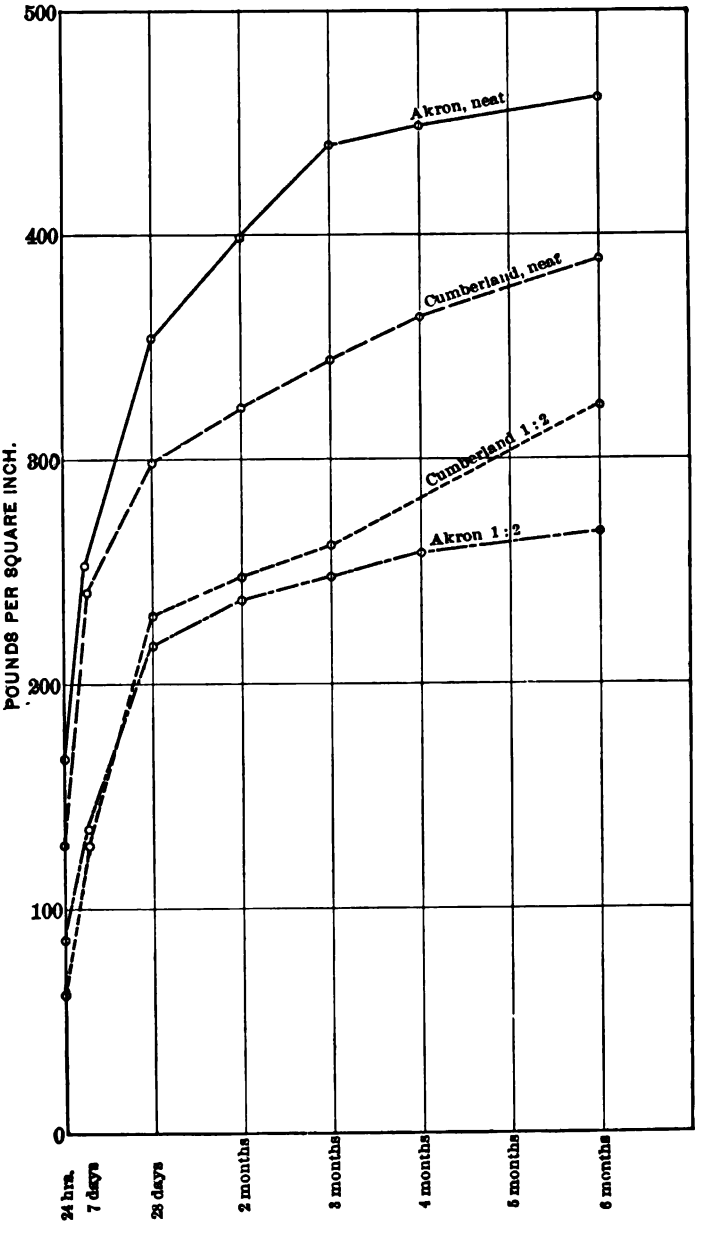


FIG. 57.—Tensile strength of Akron and Cumberland cements. (Philadelphia tests, 1897, 1898.)

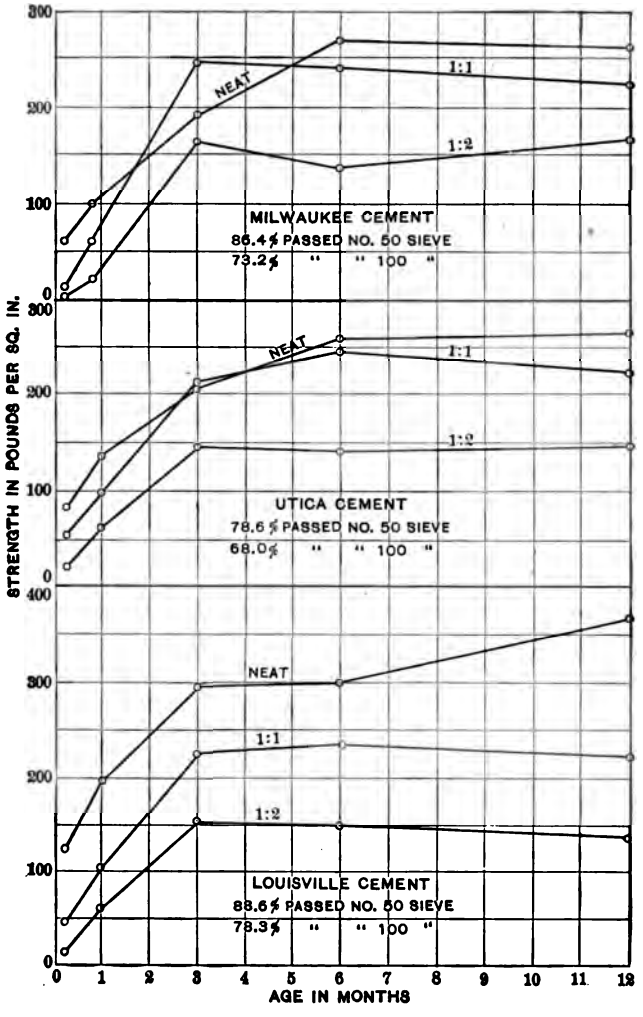


FIG. 58.*—Tensile strength of natural cements, Cairo Bridge tests.

* From Johnson's "Materials of Construction," p. 569.

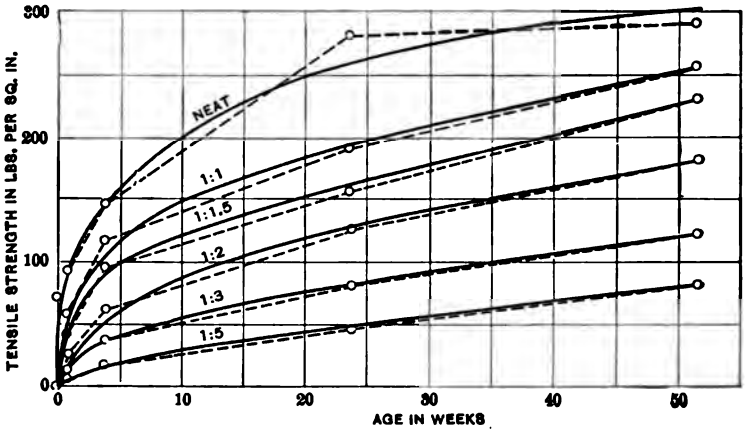


FIG. 59.*—Tensile strength Rosendale cements, Boston Main Drainage, 1885.

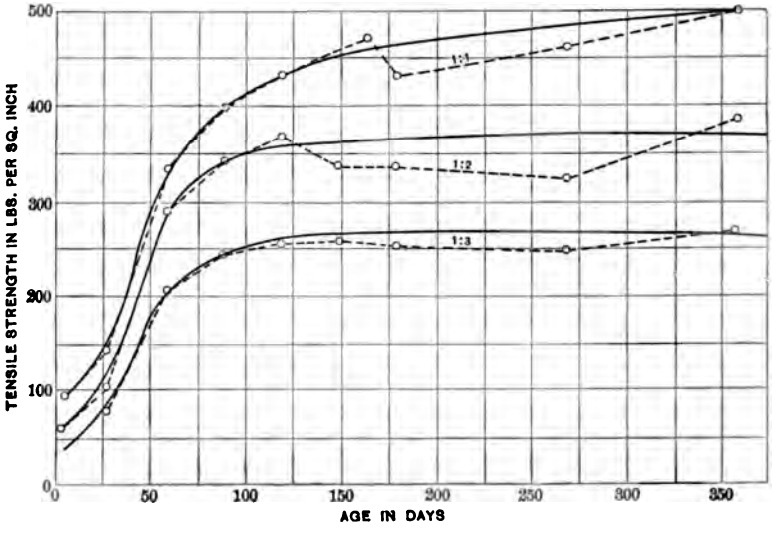


FIG. 60.†—Tensile strength natural cements, Sault Ste. Marie, 1894.

* From Johnson's "Materials of Construction," p. 568.
† Ibid., p. 570.

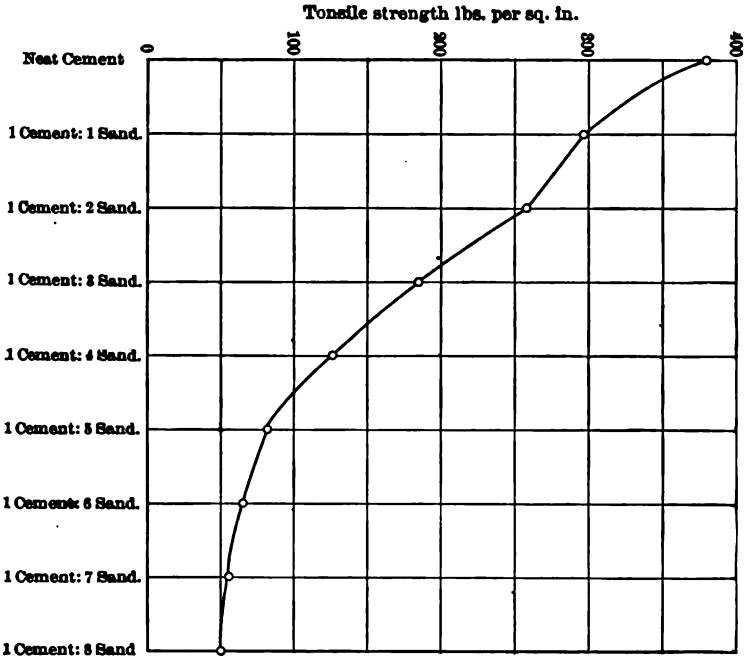


FIG. 61.—Effect of sand on tensile strength of natural cement. (Sabin.)

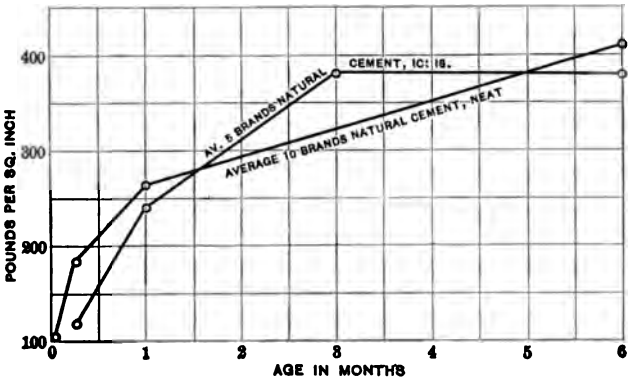


FIG. 62.*—Tensile tests, Sault Ste. Marie.

* From Johnson's "Materials of Construction," p. 571.

TABLE 136.

EFFECT OF SAND ON TENSILE STRENGTH OF NATURAL CEMENT. (SABIN.)

Composition.		Tensile Strength.		
Cement.	Sand.	Maximum.	Minimum.	Average.
1	0	428	340	380
1	1	332	251	297
1	2	298	224	260
1	3	208	144	183
1	4	154	74	128
1	5	109	61	81
1	6	81	56	69
1	7	68	32	56
1	8	66	29	53

Compressive strength.—Tests on various natural cements carried out by Clifford Richardson * are summarized in Table 137.

TABLE 137.

COMPRESSIVE TESTS OF NATURAL CEMENTS. (RICHARDSON.)

	Neat Cement.			1 Cement, 2 Sand.		
	7 Days.	28 Days.	3 Months.	7 Days.	28 Days.	3 Months.
Buffalo, N. Y.	997	1300	....	700	980	
Akron Star, N. Y.	1325	2812	....	700	1300	
Louisville, Ky.	1737	2795	....	500	1065	
Milwaukee, Wis.	913	1457	....	506	822	
Fort Scott, Kan.	769	1256	....	417	680	
" " "	1072	2402	3155	988	1470	2718
Mankato, Minn.	1663	2288	....	575	834	
Utica, Ill.	1538	1972	....	1075	1450	
Rosendale, N. Y.	....	1737	....	....	614	
Average.	1252	2002	3155	683	1024	2718

The following tests (Table 138) of compressive strength were made on 4-inch cubes at the Watertown Arsenal.†

* Brickbuilder, vol. 6, p. 253.

† Report on tests of metals, etc., at Watertown Arsenal for 1902, pp. 377-381.

TABLE 138.

COMPRESSIVE STRENGTH OF 4-INCH NATURAL-CEMENT CUBES.
(WATERTOWN ARSENAL.)

Brand.	Per Cent Water.	Compressive Strength, Lbs. per Square Inch.			
		7 Days.	1 Month.	3 Months.	12Months.
Austin, Minn	35.4	356	1090	1530	
Mankato, Minn	41.2	566	1020	1420	
Potomac, Md	39.2	423	840	1110	1100
Obelisk, Erie County, N. Y	35.8	750	1360	2220	
Norton, Ulster County, N. Y	39.6	472	880	1570	
Newark and Rosendale, Ulster County, N. Y	38.7	407	1090	1440	1590
Hoffman	36.2	464	790	1230	
Bonneville improved, Penna	38.7	620	1130	1560	

TABLE 139.

EFFECT OF HEATING ON COMPRESSIVE STRENGTH. (WATERTOWN ARSENAL.)

Brand.	Mixture.	Per Cent Water.	Age. Yrs. Mon. Days	Heated to	Compressive, Strength, Lbs. per Sq. In.
Mankato	Neat cement	38	1 2 19	Not heated	1867
"	" "	38	1 2 19	200° F.	1657
"	" "	38	1 2 19	300° F.	1877
"	" "	38	1 2 19	400° F.	1967
"	" "	48	1 2 19	500° F.	1603
"	" "	48	1 2 19	600° F.	1453
"	" "	48	1 2 19	700° F.	1497
"	" "	48	1 2 19	800° F.	1400
"	" "	48	1 2 19	900° F.	1185
"	1 cement, 1 sand	28	1 6 21	Not heated	538
"	1 " 1 "	31	1 6 21	200° F.	491
"	1 " 1 "	31	1 6 21	300° F.	433
"	1 " 1 "	28	1 6 21	500° F.	471
"	1 " 1 "	28	1 6 21	700° F.	381
"	1 " 1 "	31	1 6 21	900° F.	317
"	1 " 1 "	31	1 6 21	500° F.	329

Ratio of compressive to tensile strength.—The ratio between the compressive and tensile strength is apparently, in the natural cements, considerably lower than in Portland cement.

TABLE 140.

RELATION OF TENSILE TO COMPRESSIVE STRENGTH OF NATURAL CEMENT. (SABIN.)

Brand.	Composition.	Age.	Average Tensile Strength, Pounds per Square Inch.	Average Compressive Strength, Pounds per Square Inch.	Ratio Compressive + Tensile.
A.....	1 cement, 2 sand	28 days	116	662	5.71
B.....	1 " 2 "	28 "	187	1020	5.45
C.....	1 " 2 "	28 "	237	1175	4.96
D.....	1 " 2 "	28 "	117	550	4.70
E.....	1 " 2 "	28 "	286	1224	4.28
A.....	1 " 2 "	3 months	334	1261	3.77
B.....	1 " 2 "	3 "	294	1118	3.80
C.....	1 " 2 "	3 "	370	1698	4.59
D.....	1 " 2 "	3 "	298	1076	3.61
E.....	1 " 2 "	3 "	291	1018	3.50

Report Chief of Engineers, U. S. A., 1896, p. 2872.

The following tests were made by Prof. Creighton on samples of the Utica (Ill.) natural cement used in the construction of the drainage works at New Orleans.

TABLE 141.

RELATION OF TENSILE TO COMPRESSIVE STRENGTH OF UTICA NATURAL CEMENT. (CREIGHTON.)

Composition.	Age.	Average Tensile, Pounds per Square Inch.	Average Compressive, Pounds per Square Inch.	Ratio Compressive + Tensile.
Neat cement.....	7 days	210		
" "	14 "	255	1300	5.09
" "	28 "	270	1705	6.32
" "	2 months	283		
" "	3 "	300		
" "	6 "	340	1805	5.31
1 cement, 1 sand.....	7 days	136		
1 " 1 "	14 "	269	1170	4.35
1 " 1 "	28 "	290	1417	4.88
1 " 1 "	2 months	302	1583	5.24
1 " 1 "	3 "	....	1723	
1 " 1 "	6 "	313	1940	6.19
1 " 2 "	7 days	76		
1 " 2 "	14 "	114	568	4.98
1 " 2 "	28 "	162	655	4.05
1 " 2 "	2 months	164	840	5.12
1 " 2 "	3 "	172	1135	6.60
1 " 2 "	6 "	176	1768	10.05
1 " 3 "	7 days			
1 " 3 "	14 "	98	352	3.59
1 " 3 "	28 "	112	403	3.59
1 " 3 "	2 months	124		
1 " 3 "	3 "	131	456	3.48
1 " 3 "	6 "	138	923	6.68

Modulus of elasticity.—Tests of the modulus of elasticity of several American natural cements made at Watertown Arsenal * are summarized in Table 142.

TABLE 142.

MODULUS OF ELASTICITY.

Brand.	Composition.	Weight per Cu. Ft.	Age. Mo.	Da.	Ultimate Strength, Pounds per Sq. In.	E.	Lbs. sq. in.
Austin	Neat	100.6	2	14	610	E(100–500)	= 567,000
Newark Rosendale.	"	99.5	2	15	700	E(100–500)	= 485,000
" " "	"	120	1		.....	E(100–500)	= 988,000
" " "	"	120	5		2720	E(100–1000)	=1,818,000
						E(1000–2000)	=1,342,000
Obelisk	"	107.0	2	8	1430	E(100–500)	= 976,000
						E(500–1000)	= 826,000
"	"	116.6	2	7	1900	E(100–1000)	=1,132,000
"	1 cement 1 sand	121.9	2	5	1330	E(100–1000)	=1,146,000

* Report of tests of metals, etc., made at Watertown Arsenal, for 1902, pp. 501–505.

PART VI. PORTLAND CEMENT.

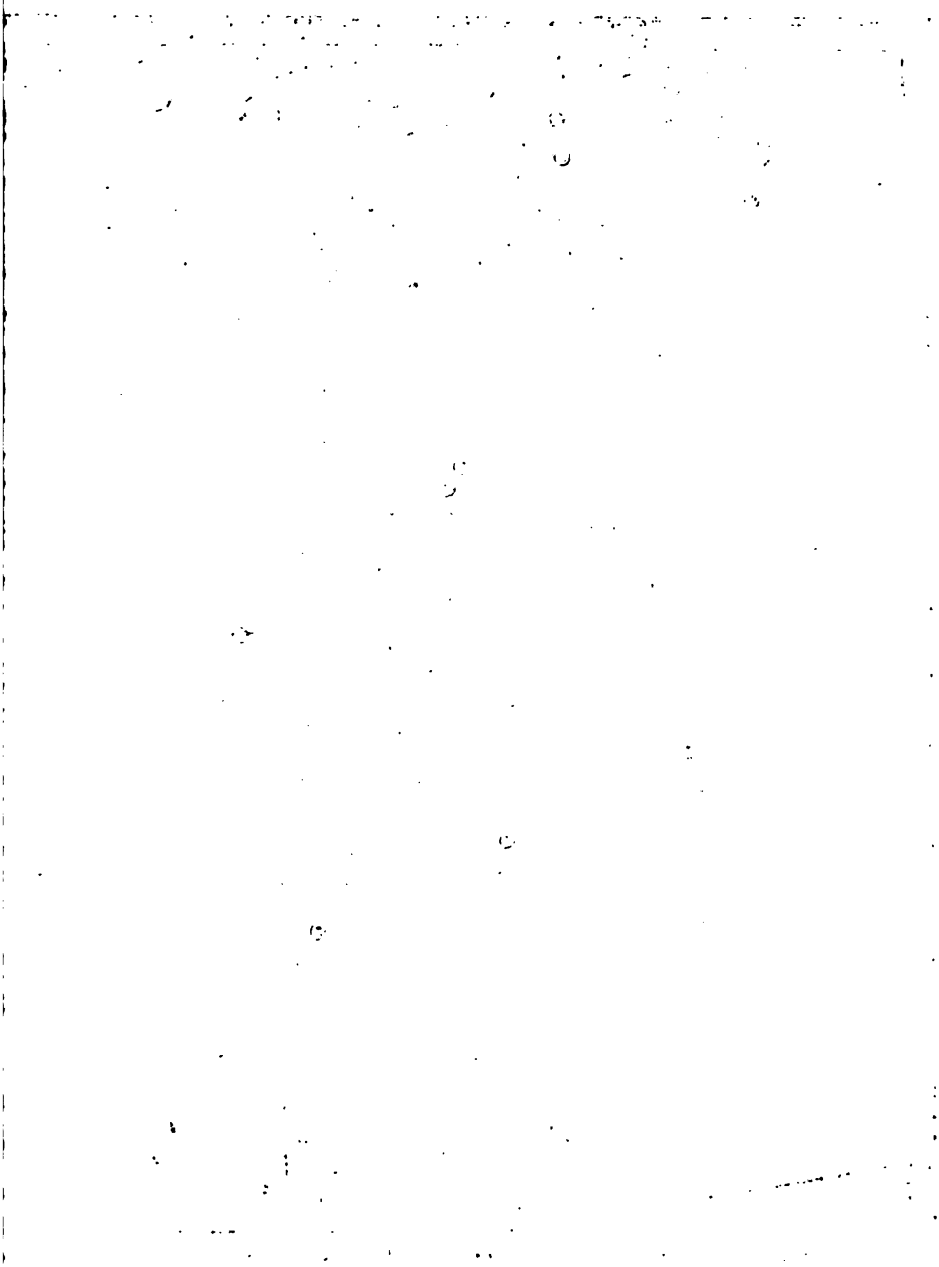
CHAPTER XX.

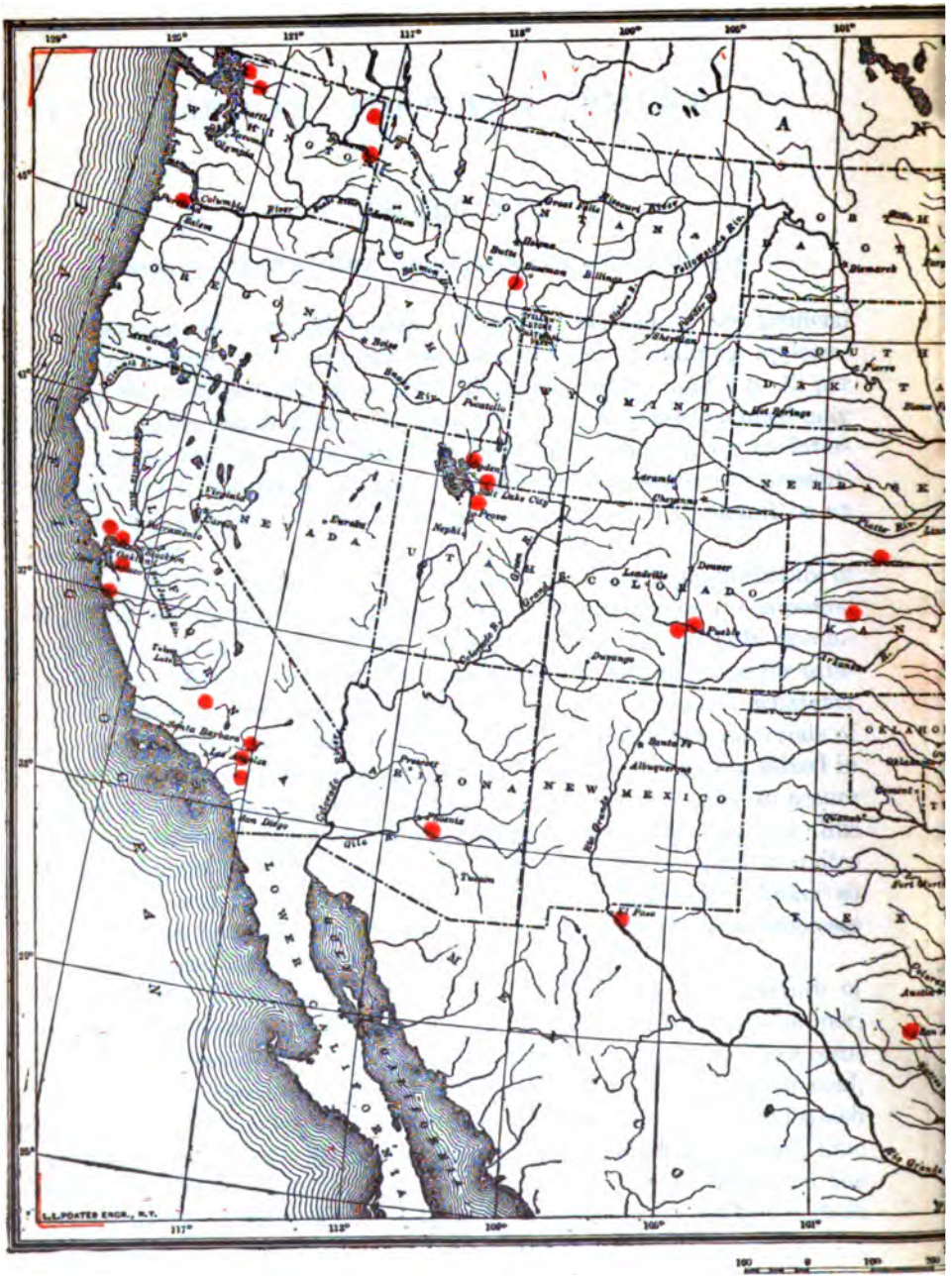
PORTLAND CEMENT: PRELIMINARY STATEMENTS.

Definition of Portland Cement.—Portland cement is an artificial chemical product of fairly definite composition, containing approximately 60 to 65 per cent lime, 20 to 25 per cent silica, and 5 to 12 per cent iron oxide and alumina. Each of the four constituents named may vary within certain limits, but these possible variations are so interrelated that it is possible to express the general composition of present-day Portland cements very closely by a formula, even though it be an empirical one.

Stages in Manufacture.—The essential feature in the manufacture of Portland cement is the formation of a fairly definite chemical compound under the action of intense heat. That this may be properly accomplished and that the compound so formed may be put in shape for utilization, three general stages in manufacture are necessary, whatever the details of the processes employed may be: First, raw materials of proper chemical and physical composition must be intimately mixed in proper proportions, drying and fine grinding being necessary to secure the very essential intimacy of the mixing; second, the raw mix thus prepared must be burned at a very high temperature until it unites chemically and physically as a clinkered mass; third, the clinker so formed must be ground very finely. The end result of these processes is the Portland cement of commerce.

Materials Used.—The raw materials used in the manufacture of Portland cement may be grouped as (1) cement materials proper, including limestone, marl, shells, cement rock, clay, shale which are combined to form the actual cement mixture; (2) fuels, including the coal, oil, or gas used to burn the cement, as well as the fuel required to furnish power for the plant; (3) fluxes and retarders, including gypsum, lime chloride, alkalies, fluorite, and the like, which may be added to the cement or the cement mixture at different stages to accomplish certain purposes.




Columbia River
Snake River
Yellowstone River
Missouri River
Great Falls
Billings
Bismarck
Boise
Pocatello
Salt Lake City
Provo
Reno
Virginia City
Carson City
Sacramento
Oakland
San Francisco
Fresno
Mojave Desert
Death Valley
Los Angeles
San Diego
Yuma
Phoenix
Tucson
Gila R.
Colorado R.
Green R.
Denver
Pueblo
Colorado Springs
Santa Fe
Albuquerque
El Paso
Rio Grande
Lower California
Gulf of California
Pacific Ocean
Nevada
Utah
Arizona
New Mexico
Colorado
Wyoming
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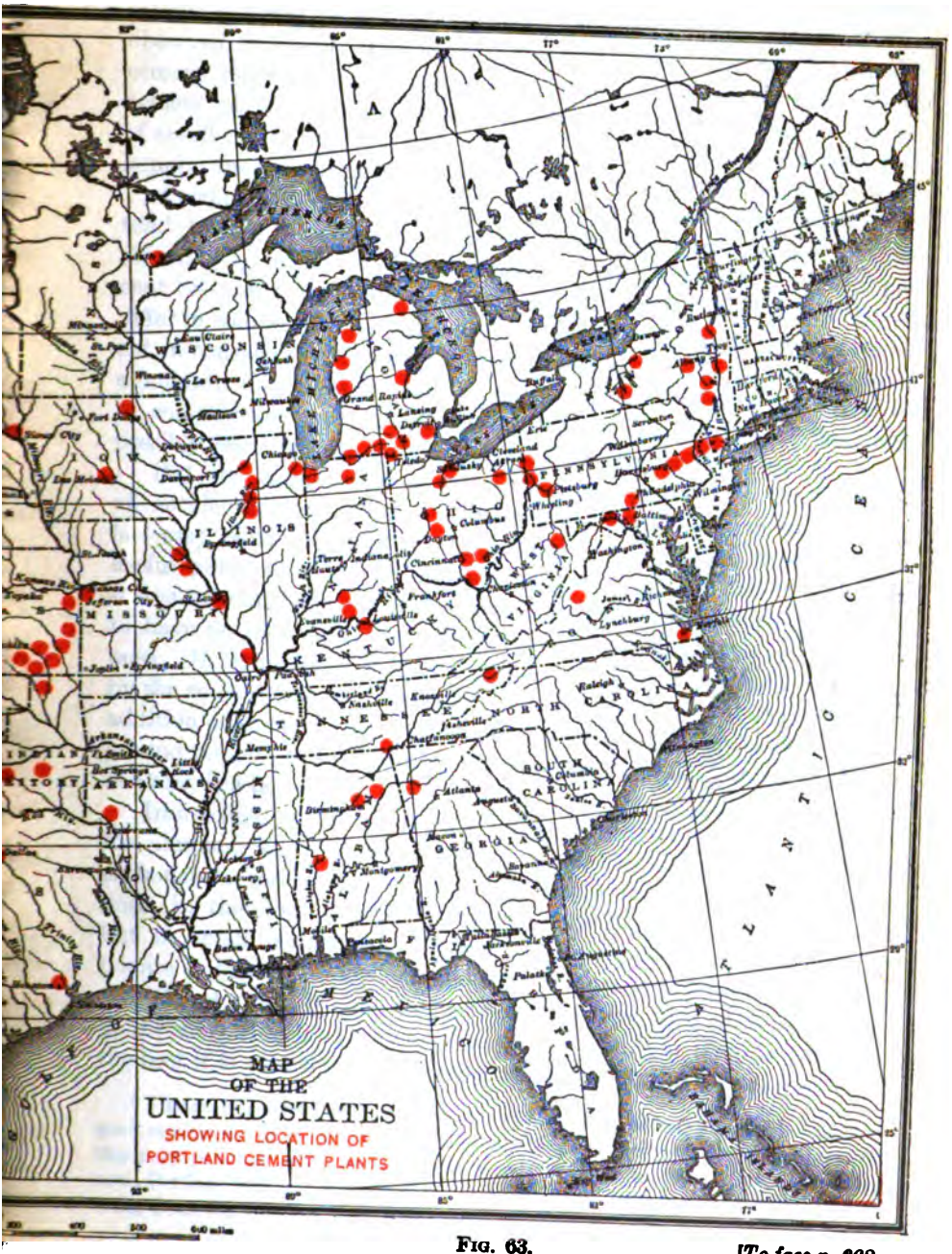

FIG. 63.

[To face p. 268.

These several classes of raw materials will be discussed later, greatest attention being paid to the cement materials proper. It should be observed, however, that this very concentration of attention on the cement materials proper has led to serious errors in the location of cement plants. 'It can hardly be stated too strongly that no degree of excellence in the limestone or shale can make up for expensive fuel supply, for poor transportation facilities, or for narrow market areas.'

Composition and constitution.—Portland cements may be said to tend toward a composition approximating to pure tricalcic silicate ($3CaO,SiO_2$) which would correspond to the proportion CaO 73.6 per cent SiO_2 26.4 per cent. Actual Portland cements as at present made differ in composition very markedly from this. Alumina is always present in considerable quantity, forming with part of the lime the tricalcic aluminate (CaO,Al_2O_3), and probably, under ordinary conditions as to composition and burning lower aluminates. Ferrites of lime and possibly ferric silicate are also present in commercial clinker.

But the composition is still further complicated by the presence of accidental impurities or intentionally added ingredients. These last may be simply adulterants, or they may be added to serve some useful purpose. Calcium sulphate is a type of the latter class. It serves to retard the set of the cement and in small quantities appears to have no injurious effect which would prohibit its use for this purpose. In dome kilns, sufficient sulphur trioxide is generally taken up by the cement from the fuel gases to obviate the necessity for the latter addition of calcium sulphate, but in the rotary kiln its addition to the ground cement, in the form of either powdered crude gypsum or plaster of Paris, is a necessity.

Iron oxide, within reasonable limits, seems to act as a substitute for alumina, and the two may be calculated together. Magnesium carbonate is rarely entirely absent from limestones or clays, and magnesia is, therefore, almost invariably present in the finished cement but in small percentage. Though magnesia, when magnesium carbonate is burned at low temperature, is an active hydraulic material (see Chapter XI) it does not normally combine with silica or alumina at the clinkering heat employed in Portland-cement manufacture. At the best it is an inert and valueless constituent in the normal Portland *

* This statement should not be construed to mean that it is impossible to make a good cement of the Portland type, but containing high percentages of magnesia, for this very possibility will be discussed on a later page (p. 360). But such a magnesia Portland will, of necessity, differ quite markedly both in preparation and properties from the lime Portlands now in use.

cement; many regard it as positively detrimental in even small amounts, and because of this feeling manufacturers prefer to carry it as low as possible. In amounts of less than 3½ per cent to 5 per cent it is certainly harmless—and American Portlands from the Lehigh district usually reach well up toward that limit. In European practice it is carried somewhat lower.

Cementation Index.—In discussing the hydraulic limes and natural cements, use has been made of the Cementation Index, a device which affords an easy means of comparing the hydraulic and other properties of various cements. In dealing with Portland cement, this device reaches its maximum of efficiency and becomes of great service in every phase of the subject, from the selection of the raw materials and the proportioning of the mix to the valuation of the finished product. In later chapters the basis and determination of the Cementation Index will be found discussed in detail. In the present chapter it is only necessary to state that its value is obtained from the following formula:

$$\text{Cementation Index} = \frac{\begin{array}{r}(2.8 \times \text{percentage silica}) + \\ (1.1 \times \text{percentage alumina}) + \\ .7 \times \text{percentage iron oxide}\end{array}}{\text{Percentage lime (CaO)} + 1.4 \text{ percentage magnesia}}.$$

This formula is applicable to raw materials as well as to cements, but the user must recollect that the first factor in the divisor is based on the percentage of lime (CaO), not of lime carbonate ($CaCO_3$), and similarly with the magnesia. It is empirical, but useful.

The Cementation Index, determined as above described, is a measure of the degree of basicity of a cement, or the relation of the acid (SiO_2,Al_2O_3,Fe_2O_3) to the basic (CaO,MgO) factors in its composition. A high cementation index means a high-limed and low-clayed cement, while a low index would mean the opposite. In Portland cements as at present made the Cementation Index will commonly fall within the limits of 1.00 and 1.20, 1.00 being the ideal index for a Portland.

Silica-alumina ratio.—The ratio between the silica and the alumina +iron oxide gives the second important index to the character of a cement. For convenience of reference this may be termed the silica-alumina ratio. This ratio, properly speaking, should take into account the different combining weights of the three compounds concerned, and would, therefore, theoretically be found from the formula.

$$\text{Acidity Index} = \frac{2.8 \times \text{percentage silica}}{(1.1 \times \text{percentage alumina}) + (.7 \times \text{percentage iron oxide})}.$$

To the value determined by this formula the term " Acidity Index " might be very properly applied. But in ordinary practice the percentage of iron oxide present is so small that the ratio between the silica and the alumina+iron is given correctly enough by simple division, i.e.,

$$\frac{\text{Percentage silica}}{\text{Percentage alumina+percentage iron oxide}}.$$

The value thus obtained will be called briefly the silica-alumina ratio (though it considers the iron oxide also). It may be said that the percentage of lime being constant, the clinkering temperature decreases with the silica-alumina ratio; while the setting-time and ultimate strength of the cement are in inverse proportion to the values of the ratio. Further than this, however, the relations between the alumina and the iron oxide are of great importance. Other things being equal, cements high in alumina are quick-setting and quick-hardening; while cements high in iron oxide are slow hardening, but attain ultimate strength.

Kinds of material used.—Before taking up the detailed discussion of the various raw materials used in the manufacture of Portland cement, some general statements on the kinds and combinations of raw materials actually in use will probably be found serviceable.

In order that the value and availability of different raw materials may be estimated, it will be convenient to assume a certain ideal composition for a cement rock. For the purposes of the present chapter this can be done in a sufficiently accurate way by considering that a Portland-cement mixture, when ready for burning, should contain about 75 per cent of lime carbonate ($CaCO_3$), and about 20 per cent of silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3) together, the remaining 5 per cent or so containing any magnesia, sulphur, and alkalies that may be present. More exact information on these points will be found in Chapter XXIX, where a somewhat detailed discussion of the calculation and composition of Portland-cement mixtures, together with a number of analyses of actual mixtures and cements, will be given.

The essential elements which enter into this mixture—lime, silica, alumina, and iron—are all abundantly and widely distributed in nature, occurring in different forms in many kinds of rocks; and it can readily be seen that, theoretically, a satisfactory Portland-cement mixture could be prepared by combining, in an almost infinite number of ways and proportions, many possible raw materials. Obviously, too, we

might expect to find perfect gradations in the degree of *artificialness* of such a mixture, varying from the one extreme where a natural rock of almost absolutely correct composition was used to the other extreme where two or more materials in nearly equal amounts were required to produce a mixture of correct composition.

The almost infinite number of raw materials which are theoretically available are, however, reduced to a very few in practice under existing commercial conditions. The necessity for producing the mixture as cheaply as possible rules out of consideration a large number of materials which would be considered available if chemical composition was the only thing to be taken into account. Some materials otherwise suitable are too scarce and consequently too expensive for such use; some are too difficult to pulverize finely and bring into combination. In consequence comparatively few combinations of raw materials are actually in use.

In certain favored localities deposits of argillaceous (clayey) limestones or "cement rock" have been found in which the lime, silica, alumina, and iron oxide exist in so nearly the proper proportions that only a relatively small amount (say 10 per cent or so) of other material, added before calcination, is required in order to make a mixture of correct composition. Certain blast-furnace slags are also close in composition to the desired mixture, and are used like "cement rock."

In the majority of plants, however, most or all of the necessary lime is furnished by one raw material, while the silica, alumina, and iron oxide are largely or entirely derived from another raw material. The raw material which furnishes the lime is usually a natural limestone—either a hard limestone, a chalk, or a marl—but occasionally an artificial product is used, such as the chemically precipitated lime carbonate which results as a waste or by-product of alkali manufacture. The silica, alumina, and iron oxide of the mixture are usually derived from clays or shales, more rarely from slates.

The various raw materials available for use in Portland-cement manufacture differ in composition, physical characters, and origin. As to *composition*, they may be almost (*a*) purely calcareous, (*b*) a mixture of calcareous and argillaceous elements, or (*c*) almost purely argillaceous; as to *physical characters* they may be (*a*) hard and massive, like the hard limestones and slates, (*b*) soft, like the chalks and shales, or (*c*) granular or unconsolidated, like the marls, clays, alkali waste, and granulated slag. As to *origin*, they may be (*a*) natural, like limestones, marls, slates, clays, etc., or (*b*) artificial, like alkali waste and furnace slag.

TABLE 143.

CHARACTER OF PORTLAND-CEMENT MATERIALS.

	Natural.			Artificial.
	Hard.	Soft.	Unconsolidated.	Unconsolidated.
Calcareous ($CaCO_3$ over 80%)	Pure hard limestone	Pure soft limestone or pure chalk	Pure marl Shells.	Alkali waste
Argillo-calcareous ($CaCO_3$ 40 to 80%)	Hard clayey limestone (cement rock)	Soft limestone or clayey chalk	Clayey marl	Blast-furnace Slag
Argillaceous ($CaCO_3$ less than 40%)	Slate	Shale	Clay	Coal-ash

A glance at the tabulation above will show the relative physical and chemical characters of the different raw materials. It is obvious, if 75 per cent of lime carbonate will make a good cement mixture, that any of the materials in the middle line (i.e., the Argillo-calcareous group) could be used as a basis and its composition corrected by adding either a purely calcareous material or a purely argillaceous material, as might be necessary. The cement practice in the Lehigh district is an example of this kind of mixing. But the same result could be obtained by mixing any one of the materials on the first line of the table (i.e., the Calcareous group) with any one of the argillaceous materials listed in the bottom line. This is the method followed at most plants outside of the Lehigh district. There is really little to choose between the two kinds of mixtures, for the final result is the main thing. In later pages the few differences that do exist are pointed out and the advantages and disadvantages of each type are mentioned.

In previous papers the writer has grouped, under six heads, the various combinations of raw materials at present used in the United States in the manufacture of Portland cement. This grouping is as follows:

(1) Argillaceous hard limestone (cement rock) and pure limestone.
(2) Pure hard limestone and clay (or shale).
(3) Soft (chalky) limestone and clay (or shale).
(4) Marl and clay (or shale).
(5) Alkali waste and clay.
(6) Slag and pure limestone.

The relative commercial importance of these different combinations is indicated by the figures as to output.

Examination of the statistics available, which have been arranged by the writer from figures given in the various volumes on "Mineral Resources of the United States," issued by the U. S. Geological Survey, will develop several facts of interest. In the first place it will be seen that the "cement-rock" type of mixture, important because of its use in the Lehigh district, is slowly decreasing in relative importance, having fallen from almost three-fourths of the total product in 1898 to only a little over one-quarter the total product in 1918. In absolute number of barrels produced per year, it is of course still increasing, but it is no longer the main type of material to be considered.

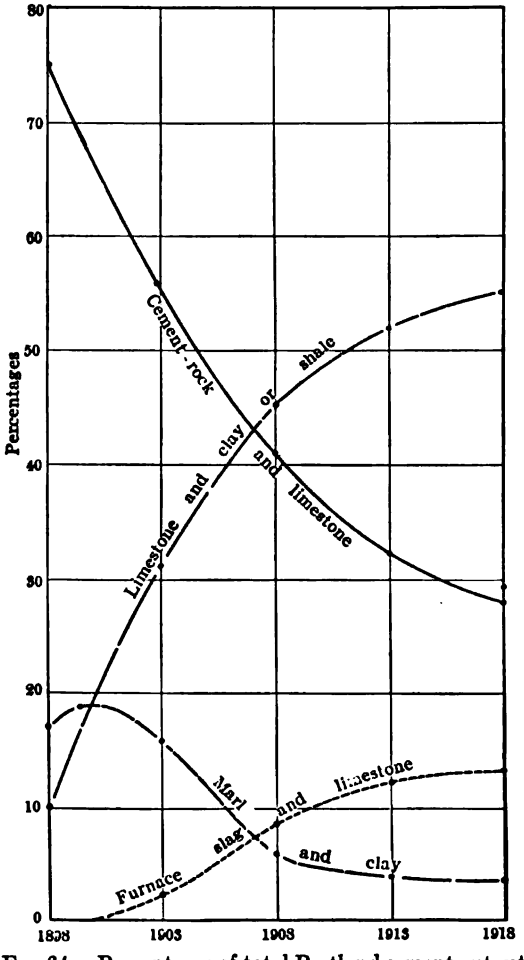

FIG. 64.—Percentages of total Portland cement output produced from different raw materials, 1898–1918.

The use of marl as a cement material is also slowly decreasing in relative importance, having reached its point of maximum output in 1899, when it supplied almost one-fifth of all the cement made. The hard limestones, on the other hand, have increased steadily in importance from 1898, when they produced less than one-tenth of the whole output, to the present time, when they produce well over half.

Quantity of raw materials necessary.—The qualities necessary in

each raw material will be later discussed, but here it will be useful to briefly consider the quantities necessary for a Portland-cement plant.

We may assume, without substantial error, that for each thousand barrels of daily output a plant will use 225 tons of limestone, 75 tons of clay or shale, 100 tons of coal (for kilns and power), and 5 tons of gypsum.

For a year's output on the basis of 300 days run, the plant will need for each 1000-barrels daily production:

67,500 tons of limestone yearly;
22,500 tons of clay or shale;
30,000 tons of coal;
1,500 tons of gypsum.

The coal and gypsum, unfortunately, will commonly be bought in the open market; that is a matter which few cement companies have as yet developed properly, as have the steel companies. But for the raw materials proper—the limestone and the clay—those will in practically all cases be quarried by the cement company from its own properties. The yearly supply needed will use up, on the basis of limestone weighing 160 pounds per cubic foot and shale weighing 125 pounds dry;

For each 1000-barrels daily output, the plant will use per year

20 acre-feet of limestone;
8½ acre-feet of clay or shale.

Since it would hardly pay to locate a plant on a property containing less than a twenty-year supply (and this is really cutting it very fine under ordinary conditions as to profits), the property should of necessity contain:

For each 1000-barrels daily output:

400 acre-feet of limestone;
170 acre-feet of clay or shale.

CHAPTER XXI.

LIMESTONES.

THE Portland-cement materials which are discussed in this and the following chapters (XXII, XXIII), under the names of pure hard limestone, chalk, argillaceous limestone, or " cement rock," and marl, agree in that they are all forms of limestones, though they differ sufficiently in their physical, chemical, and economic characters to be discussed separately and under different names. In order to avoid unnecessary repetition, no general discussion of limestone will be presented here but reference should be made to Chapter VI, where the origin, varieties, composition, and properties of limestones are described in detail. In the present chapter these general facts will be briefly summarized, and certain features common to all the types of limestone used in Portland-cement manufacture will be noted, after which these different types will be separately discussed.

Limestones in General.

Varieties and origin.—Limestones are rocks composed largely or entirely of lime carbonate, or of lime carbonate with magnesium carbonate. Though one or both of these carbonates will necessarily be the principal ingredients in the rock, various impurities may occur. In addition to the chemical differences which are thus caused between different samples or kinds of limestone, they may also differ in their physical characters, or in their methods of origin, or in both of these points.

Limestones are primarily formed by the deposition of lime carbonate from sea- or lake-water which carries this salt in solution. This deposition may be direct, caused by chemical processes, or it may be effected through the agency of living organisms. *Travertine* and *tufa* are chemically deposited limestones formed by surface waters. Molluscs are able to abstract lime carbonate from sea-water and utilize it in the formation of their shells. On the death of the animals, these shells sink to the sea-bottom and thus aid in the formation of calcareous deposits. Microscopic organisms acting in this way are the cause of the forma-

tion of *chalk*, as noted later (p. 287). Vegetable life, acting in a more indirect way, appears to be an important agency in the deposition of *marl* (p. 306). Ordinary limestones may have originated in any of the ways noted above. After their formation, if subjected to sufficient heat and pressure, normal limestones may be converted into *crystalline limestones* or *marbles*.

All the varieties of limestone above named may vary in composition and degree of purity within wide limits.

Composition of limestones.—The term limestone is used, in its most general sense, to include all rocks composed largely or entirely of lime carbonate, or of lime carbonate *plus* magnesium carbonate.* A limestone of ideal purity will of course consist of 100 per cent of these carbonates; but few limestones attain even approximate purity and many are very impure. As the percentage of impurities increases, the limestone becomes more and more clayey or sandy or shaly, until at last the name limestone is no longer applicable. The exact lower limit of the group it would be difficult to fix, because the change is gradual, but probably all would agree that a rock containing less than 40 per cent of carbonates can hardly be called a limestone, but should rather be termed a calcareous clay or sandstone or shale, as the case may be. In the present volume, therefore, the lower limit in composition of limestones will be accepted as that above noted—i.e., 40 per cent of carbonates.

As the average composition of a good Portland-cement mixture is about three-fourths lime carbonate and one-fourth clayey matter, it is obvious that such a composition could be secured either by mixing a pure limestone and a pure clay in the proportions of about three parts limestone and one part clay, or by starting with a clayey limestone carrying, say, 60 to 85 per cent lime carbonate and adding enough clay or pure limestone to bring this percentage up or down to the required 75 per cent. The " cement rock " of the Lehigh district is an example of a highly argillaceous limestone, usually too low in lime carbonate to be a good Portland-cement material of itself and requiring the addition of a relatively small percentage of pure limestone. At a few Lehigh district quarries, however, the " cement rock " is a little too high in

* When discussing Portland-cement materials, the term "limestone" may be still further restricted so as to entirely exclude the highly magnesian limestones. At present all the Portland cement made is kept as low in magnesia as possible, because of the fear that this ingredient may do some harm to the cement. As a cement carrying over 5 per cent of magnesia (MgO) would be hard to market, a limestone carrying over 6 to 8 per cent of magnesium carbonate ($MgCO_3$) can hardly be classed as a possible Portland-cement material at present.

carbonate, rather than too low, so that it requires the addition of clay and not of limestone.

In the present volume the term "cement rock" will be used to cover clayey limestones low in magnesia and carrying from 50 to 80 per cent or so of lime carbonate, while limestones higher than 80 per cent in carbonate will be called for convenience "pure limestones."

Impurities of limestone.—Whether a limestone consists entirely of calcium carbonate or carries more or less of magnesium carbonate in addition, it may also contain a greater or lesser amount of distinct impurities. From the point of view of the Portland-cement manufacturer, the more important of these impurities are silica, alumina, iron, alkalies, and sulphur, all of which have a marked effect on the value of the limestone as a cement material. These impurities will therefore be discussed in the order in which they are named above.

The silica in a limestone may occur either in combination with alumina as a clayey impurity or not combined with alumina. As the effect on the value of the limestone would be very different in the two cases, they will be taken up separately.

Silica alone.—Silica, when present in a limestone containing no alumina, may occur in one of three forms, and the form in which it occurs is of great importance in connection with cement manufacture.

(1) In perhaps its commonest form, silica is present in nodules, masses, or beds of flint or chert. Silica occurring in this form will not readily enter into combination with the lime of a cement mixture, and a cherty or flinty limestone is therefore almost useless in cement-manufacture.

(2) In a few cases, as in the hydraulic limestone of Teil, France, a large amount of silica is present and very little alumina, notwithstanding which the silica readily combines with the lime on burning. It is probable that in such cases the silica is present in the limestone in a very finely divided condition, or possibly as hydrated silica, possibly as the result of chemical precipitation or of organic action. In the majority of cases, however, a highly siliceous limestone will not make a cement on burning unless it contains alumina in addition to the silica.

(3) In the crystalline limestones (marbles) and less commonly in uncrystalline limestones, whatever silica is present may occur as a complex silicate in the form of shreds of mica, hornblende, or other silicate mineral. In this form silica is somewhat intractable in the kiln and mica and other silicate minerals are therefore to be regarded as inert and useless impurities in a cement rock. These silicates will flux at a lower temperature than pure silica and are thus not so trouble-

some as flint or chert. They are, however, much less serviceable than if the same amount of silica were present in combination with alumina as a clay.

Silica with alumina.—Silica and alumina, combined in the form of clay, are common impurities in limestones, and are of special interest to the cement manufacturer. The best-known example of such an argillaceous limestone is the cement rock of the Lehigh district of Pennsylvania. Silica and alumina, when present in this combined form, combine readily with the lime under the action of heat, and an argillaceous limestone therefore forms an excellent basis for a Portland-cement mixture.

Iron.—Iron when present in a limestone occurs commonly as the oxide (Fe_2O_3) or sulphide (FeS_2); more rarely as iron carbonate or in complex silicate. Iron in the oxide, carbonate, or silicate forms is a useful flux, aiding in the combination of the lime and silica in the kiln. When present as a sulphide in the form of the mineral pyrite it is to be avoided in quantities over 2 or 3 per cent.

Alkalies.—Soda and potash occur usually in small percentages and most commonly in the looser-textured limestones. It is probable that these alkalies are largely driven off in the kiln, so that they do no particular harm to the cement under ordinary burning conditions in rotary kilns, though in the old-style dome kilns the alkalies probably remained in large part in the cement. At present indeed the alkalies in the mix yield a certain amount of recoverable potash salts at some plants.

Sulphur.—Sulphur may occur combined with lime as lime sulphate, or combined with iron as the mineral pyrite. In either case it is an injurious impurity, and the presence of over 1 to 1½ per cent of total sulphur should cause the rejection of the raw material.

Physical characters of limestones.—In texture, hardness, and compactness the limestones vary from the loosely consolidated marls through the chalks to the hard, compact limestones and marbles. Parallel with these variations are variations in absorptive properties and density. The chalky limestones may run as low in specific gravity as 1.85, corresponding to a weight of, say, 110 pounds per cubic foot, while the compact limestones commonly used for building purposes range in specific gravity between 2.3 and 2.9, corresponding approximately to a range in weight of from 140 to 185 pounds per cubic foot.

From the point of view of the Portland-cement manufacturer these variations in physical properties are of economic interest chiefly in their bearing upon two points: the percentage of water carried by

the limestone as quarried, and the ease with which the rock may be crushed and pulverized. To some extent the two properties counterbalance each other, for the softer the limestone the more absorbent it is likely to be. These purely economic features will be discussed in more detail in later chapters.

Effect of heating on limestone.—On heating a non-magnesian limestone to or above 850° C., its carbon dioxide will be driven off, leaving quicklime (calcium oxide, CaO). If a magnesian limestone be simi-

FIG. 65.—Working thick limestone-bed.

larly treated, the product would be a mixture of calcium oxide and magnesium oxide (MgO). The rapidity and perfection of this decomposition can be increased by passing steam or air through the burning mass. In practice this is accomplished either by the direct injection of air or steam, or more simply by thoroughly wetting the limestone before putting it into the kiln.

If, however, the limestone contains an appreciable amount of silica, alumina, and iron, the effects of heat will not be of so simple a character. At temperatures of 800° C. and upwards these clayey impurities will combine with the lime oxide, giving silicates, aluminates, and related salts of lime. In this manner a natural cement will be pro-

duced. An artificial mixture of certain and uniform composition burned at a higher temperature will give a Portland cement the details of whose manufacture are discussed in the present section of this book.

Pure Hard Limestones.

Under this heading are grouped limestones of normal hardness (excluding the soft chalky limestones and the marls) which carry no less than 80 per cent of lime carbonate and less than 6 per cent of magnesium carbonate. Limestones carrying less than 80 per cent of lime carbonate are described in the next chapter under the heading of Cement Rock. The boundary between the two classes is of course an arbitrary limit, and 80 per cent of $CaCO_3$ has been selected for convenience. As a matter of fact, most of the limestones used in cement-plants are much purer than the lower limit above fixed, ranging usually from 90 to 95 per cent of lime carbonate.

Soon after the American Portland-cement industry had become fairly well established in the Lehigh district, attempts were made in New York State to manufacture Portland cement from a mixture of pure limestone and clay. These attempts were not commercially successful, and although their lack of success was not due to any defects in the limestone used, a certain prejudice arose against the use of the hard limestones. In recent years, however, this has disappeared, and a very large proportion of the American output is now made from mixtures of limestone with clay or shale. (See page 274 for comparative figures.) This reestablishment in favor of the hard limestone is doubtless due in great part to recent improvements in grinding machinery, for the purer limestones are usually much harder than argillaceous limestones like the Lehigh district " cement rock."

Composition of hard limestones actually used.—In Table 144 analyses of a large number of limestones used at American cement-plants are given. On examination it will be seen that most of these limestones range from 49 to 54 per cent of lime (CaO) and thus represent quite pure rocks, since a theoretically pure limestone composed entirely of lime carbonate ($CaCO_3$) will contain only 56 per cent of lime (CaO), the remaining 44 per cent being carbon dioxide (CO_2). With few exceptions the limestones analyzed carry less than 1 per cent of magnesia (MgO). Their sulphur percentages are also low, which appears to be more commonly the case in dealing with a hard limestone than when a soft limestone or marl is in question. The same may be said in regard to alkalies.

TABLE 144.

ANALYSES OF HARD LIMESTONES USED AT AMERICAN CEMENT-PLANTS.

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Sulphur trioxide (SO_3).	Carbon dioxide (CO_2).	Water.
1	1.21	0.70	0.50	53.62	0.44	0.11	42.98	
2	0.98	0.58	0.34	54.17	0.13	0.21	42.96	
3	1.02	1.91		53.36	0.39	0.12	43.01	
4	1.93	2.37		53.15	tr.	n. d.	42.46	
5	1.46	2.15		53.62	tr.	n. d.	42.85	
6	2.12	0.28	0.50	54.06	0.77	n. d.	42.34	
7	6.06	3.92		49.46	0.91	0.10	39.06	
8	8.20	1.30		49.37	0.85	n. d.	39.72	
9	7.54	3.43		45.57	4.36	....	39.57	
10	5.06	2.32		48.29	3.66	....	41.05	
11	13.89	2.61		45.91	1.00	....	36.82	
12	5.43	1.43		52.02	1.11	....	40.24	
13	0.74	0.13		52.49	1.87	....	43.68	
14	0.89	0.38	0.25	54.48	0.36	....	43.40	
15	0.87	0.34	0.13	54.68	0.32	....	43.44	
16	0.86	0.29		55.74	0.51	....	42.76	0.04
17	1.00	0.9	2.0	51.10	1.4	....	43.5	
18	1.19	0.95	1.28	53.13	1.36	tr.	42.66	
19	1.1	1.8		51.7	2.0	0.1	43.3	
20	0.83	1.07		52.67	1.67	....	43.19	
21	1.54	2.06		52.85	0.65	....	42.23	
22	4.17	1.37		49.34	2.94	....	41.94	
23	0.95	0.50		53.94	0.91	....	43.38	
24	3.12	1.15		52.06	1.07	....	42.06	
25	0.40	0.44		54.87	0.20	....	43.34	
26	0.54	0.42		54.73	0.19	....	43.22	
27	0.24	0.38		55.46	0.26	....	43.86	
28	1.54	0.39	1.04	53.87	0.52	....		
29	3.12	0.93		52.58	0.80	0.24	42.17	
30	2.70	1.64		52.18	1.28	0.17	42.39	
31	9.72	4.20	0.48	47.11	0.66			
32	6.30	3.35		50.25	0.22			
33	7.88	4.01		48.10	0.53			
34	3.30	1.30		52.15	1.58	0.30	40.98	
35	0.06	0.63	1.03	53.86	....	....	43.20	
36	3.53	1.14		54.45	0.44	....	38.74	
37	4.20	1.61	1.90	50.66	0.73	0.23	40.60	
38	1.30	0.73	1.17	53.34	0.75	0.03	42.72	
39	9.46	2.45	2.73	45.70	0.99	1.36	36.98	
40	0.56	1.23	0.29	54.45	0.36	tr.	43.17	
41	4.50	0.20	1.77	49.31	0.75	0.06	40.54	2.59
42	4.14	0.21	1.77	50.16	0.42	0.20	39.87	2.03
43	2.31	0.24	1.18	52.04	0.43	0.17	41.72	1.65
44	5.52	2.97		49.66	0.78			
45	n. d.	n. d.	n. d.	54.3	0.7	....	43.63	

1–5. Pacific P. C. Co., Suisun, Calif. C. J. Wheeler, analyst.
6. Southern States P. C. Co., Rockmart, Ga. J. F. Davis, analyst.
7. Chicago P. C. Co., Oglesby, Ill. Quoted in manufacturers' circular.
8. Marquette C. Co., Oglesby, Ill. 20th Ann. Rep. U. S. G. S., pt. 6, p. 544.
9–12. German-American P. C. Works, La Salle, Ill. W. E. Prüssing, analyst.
13. Lehigh P. C. Co., Mitchell, Ind. F. W. Clarke, analyst.
14–15. Bedford P. C. Co., Bedford, Ind. A. W. Smith, analyst. 20th Ann. Rep. U. S. Geol. Survey, pt. 6, p. 381.

16. Iola P. C. Co., Iola, Kansas. H. N. Stokes, analyst. Bull. 78, U. S. Geol. Survey, p. 124.
17-18. Iola P. C. Co., Iola, Kansas.
19. Kansas P. C. Co., Iola, Kansas.
20-24. Alpena P. C. Co., Alpena, Mich.
25-26. Atlas P. C. Co., Ilasco, Mo.
27. Atlas P. C. Co., Ilasco, Mo. E. Davidson, analyst.
28. Catskill P. C. Co., Smith's Landing, N. Y.
29-30. Helderberg P. C. Co., Howe's Cave, N. Y. Black, analyst.
31-33. Cayuga P. C. Co., Portland Point, N. Y. J. H. McGuire, analyst.
34. Glens Falls P. C. Co., Glens Falls, N. Y. Mineral Industry, vol. 6, p. 97.
35. Ironton P. C. Co., Ironton, Ohio. C. D. Quick, analyst.
36. Alma P. C. Co., Wellston, Ohio. 21st Ann. Rep. U. S. Geol. Survey, pt. 6, p. 402.
37-39. Diamond P. C. Co., Middle Branch, Ohio. E. Davidson.
40. Wellston, P. C. Co., Wellston, Ohio. W. S. Trueblood, analyst.
41-44. Crescent P. C. Co., Wampum, Pa. Robertson Bros., analysts. Report Q. Q., Penna. Geol. Surv., p. 107.
45. Virginia P. C. Co., Craigsville, Va. Cement Industry, p. 235.

In prospectuses and in the reports of "cement experts" analyses of limestones averaging 98 or 99 per cent of lime carbonate are quite common, but in real life a quarry that will steadily turn out limestone 94 per cent pure is about as good as can be hoped for. With a limestone of this degree of purity little attention need be paid to the character of the remaining 6 per cent of impurities. But when a limestone carrying 90 per cent or less of lime carbonate (equivalent to about 50 per cent of lime) is in use or under consideration, the character of the impurities becomes of the first importance.

Of course objectionable percentages of sulphur compounds or magnesia would be enough to debar a limestone from use, but even when the impurity consists of clayey matter (silica, alumina, and iron oxide) its exact composition is a matter of importance and should be carefully studied. The matter of interest is the ratio given for the formula

$$\frac{\text{Percentage silica } (SiO_2)}{\text{Percentage alumina } (Al_2O_3) + \text{percentage iron oxide } (Fe_2O_3)}.$$

It is to be noted that the importance of this question increases as the limestone becomes less pure. The reason for this is obvious. Suppose we are dealing with two limestones of respective composition:

	A.	B.
Lime carbonate	95.00	80.00
Silica	4.00	16.00
Alumina	0.70	2.80
Iron oxide	0.30	1.20

The ratio $\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ will in each case give a value of 4.0; but the result to the cement manufacturer will be very different. If he uses limestone *A*, its silica-alumina ratio is of little importance, for as the limestone is very pure (95 per cent $CaCO_3$) it will require the addition of considerable clay. The silica-alumina ratio of the mix will there-

fore be determined by that of the clay, not by the ratio shown by the limestone; and the manufacturer can select a clay which will give whatever he considers a desirable ratio for the mix.

But if he should use limestone *B*, it would require but little clay, since it is already very clayey; and it would be almost impossible to find a clay sufficiently aluminous to reduce the $\frac{SiO_2}{Al_2O_3+Fe_2O_3}$ ratio much below the 4.0 which is fixed by the limestone.

FIG. 66.—Working heavy horizontal bed of limestone.

For this reason it may be taken as a safe rule that when a limestone carries less than 90 per cent of lime carbonate it should give a value of between 2.25 and 3.0 for the ratio $\frac{SiO_2}{Al_2O_3+Fe_2O_3}$. These are comfortable limits, and will give the manufacturer considerable latitude in his choice of a clay to mix with it.

Prospecting and examining limestone deposits.—The prospector looking for a deposit of good limestone, or the engineer engaged to report on a deposit already located, should both realize that much trouble can be avoided if they will first familiarize themselves with the work that has been done by geologists in the areas under consider-

ation. Most states now have geological surveys, and there are few important limestone deposits that have not been located and examined by these organizations or by the Federal survey. Numerous reports on these subjects have been issued by State or Federal Geological Surveys, and these reports can usually be obtained free or at a merely nominal price on application to the proper officials. If such a report can be obtained covering the area to be examined it will do away with a lot of preliminary work on the part of the prospector or engineer.

Preliminary Examination.—In commencing work, it is desirable to prepare a rough map of the area. For this purpose high accuracy is not required, and a pocket compass or Brunton compass, with a Locke level, and a small protractor will be the only instruments required. With these a map can be made and plotted on a scale of 50 or 100 feet to the inch, distances being measured by pacing. The location of any natural outcrop, pits, wells, road or railroad cuts, and streams should be shown on the map, and their relative elevations ascertained as exactly as possible. When the rocks are lying almost horizontally, the locations of the outcrops are of far less importance than their elevations.

If there are sufficient good exposures of the rock, in either natural or artificial cuts, samples should be collected from these outcrops. The weathered part of the rock should be rejected, care being taken that the samples represent the fresh, undecomposed rock. When the natural exposures are not satisfactory, it will be necessary to secure samples by trenches, pits, or boring.

Most of the limestones with which the cement manufacturer may have to deal occur in beds or layers which are practically horizontal. In the Appalachian and other disturbed districts, however, the beds may be tilted to a considerable angle with the horizontal, and in rare cases they may even be almost vertical. Usually samples from different parts of the same bed (within reasonable distances of each other) will be very similar in composition; but, on the contrary, two adjoining beds may differ greatly from each other.

In sampling, therefore, it is desirable to collect at least one specimen from each bed or layer, noting the thickness and position of the bed. Even thin beds should not be neglected, for a thin layer of highly magnesian rock might prove a serious drawback to the economical working of the quarry if its presence were unsuspected.

When the beds are horizontal or nearly so a stream gorge or road cut may furnish a good idea of the character of the different beds. In default of such an exposure, it will be necessary to sink test pits to

the rock, unless it is exposed conveniently at the surface, and then secure samples from various depths by drilling. Whenever possible the diamond-drill is the most satisfactory exploring device, for it is practically an automatic sampler.

When the beds are steeply inclined, a trench cut across at right angles to the bedding will expose a series of beds and enable each to be sampled.

If the beds are horizontal or nearly so, and the various samples show little difference in composition, such a preliminary examination as is described above may be all that is required. In case the rock-beds dip at high angles, or if folds or faults are suspected, it will be safest to call in a geologist or mining engineer as associate. If the analyses disagree markedly, it will be advisable to undertake a more detailed examination of the area.

Detailed Mapping and Sampling.—A much more detailed examination is always desirable before the actual erection of the plant is commenced. Such an examination will decide the best possible location for the quarry, and should also give data which will aid in keeping a uniform mix.

For these purposes a contour map, with 1-, 5-, or 10-foot contours, according to the slope, on a scale of 25 feet to the inch, should be carefully prepared. The area to be examined should be laid out in 25- or 50-foot squares and their corners marked and numbered to correspond to their locations on the map. At least three good points should be selected as permanent bench-marks, far enough away from the prospective quarry-site as not to be disturbed by excavation or blasting, and the locations and elevations of these points should be carefully determined and placed on the map.

Sampling should now be taken up carefully. For final work this can be done satisfactorily only with the diamond drill. Drill-holes should be put down at every corner of the 50-foot squares. Each 5 feet of the core should be sampled and analyzed separately, to a depth of at least 50 feet. If the rock dips steeply, or if for any other reason a deep, narrow quarry seems probable, the drilling should be continued to 200 feet. If the cores from adjacent bore-holes give closely similar analyses, closer drilling is not necessary. But if two samples taken at the same depth from two adjoining holes show differences of more than 3 per cent in their lime carbonate, or more than 1½ per cent in silica, alumina, iron oxide, or magnesium carbonate, it will be best to drill at the intermediate 25-foot point.

With the data thus obtained operations can be conducted with

some confidence. Sections should be plotted to correspond to each row of drill-holes, and at the proper vertical points the drill record should be shown graphically, using different colors or conventions to distinguish rocks of different composition. The direction and amount of dip or slope of the rock-beds can be determined from observation of natural outcrops; and this will guide the engineer in drawing lines on the sections to connect the different borings.

The sections or profiles will serve as a basis for determining the amount and location of the different grades of rock. In this connection it will be safe to assume a weight of 160 pounds per cubic foot for limestone in the quarry, and to recollect that *one thousand barrels a day output will use up about* 850,000 *cubic feet of limestone per year.* This corresponds very closely to 20 acre-feet of limestone a year for each thousand barrels of daily output.

Chalk and Other Soft Limestones.

Chalk, properly speaking, is a pure carbonate of lime composed of the remains of the shells of minute organisms, among which those of Foraminifera are especially prominent. The chalks and soft limestones discussed in this chapter agree not only in having usually originated in this way, but also in being rather soft and therefore readily and cheaply crushed and pulverized. As Portland-cement materials they are therefore almost ideal. One defect, however, which to a small extent counterbalances their obvious advantages is the fact that most of these soft, chalky limestones absorb water quite readily. A chalky limestone which in a dry season will not carry over 2 per cent of moisture as quarried may in consequence of prolonged wet weather show as high as 15 or 20 per cent of water. This difficulty can of course be avoided if care be taken in quarrying to avoid unnecessary exposure to water and, if necessary, to provide facilities for storing a supply of the raw materials during wet seasons. It can be treated even more simply by adopting the wet method of manufacture, which with kilns 175 feet long or over gives very economical results.

Origin of chalk.—The term chalk is properly applied to a fine-grained and usually very pure limestone, formed largely or entirely of the calcareous shells of microscopic organisms. These shells are chiefly of the minute Foraminifera, though equally small and smaller calcareous particles of various shapes also occur. Calvin describes * a section of chalk from Iowa as follows:

* Reports Iowa Geological Survey, vol. 3, p. 224. 1895.

" In thin sections under the microscope the unbroken shells of Foraminifera are very conspicuous. They lie in close proximity to each other, and their inflated chambers, filled with crystals of calcite, sometimes occupy more than one-third the area of the entire field. It is certain that more than one-fourth, and in some instances more than one-third, of the volume of the chalk is composed of foraminiferal shells still practically entire. The matrix in which the shells are embedded is made up of a variety of objects, the most numerous and the most conspicuous under proper amplification being the circular or elliptical calcareous discs known as coccoliths. The small rodlike bodies to which the name rhabdoliths has been applied are not very common, although their pressure is easily detected with a moderately high-power objective. Mingled with coccoliths and rhabdoliths are numerous fragments that are evidently the débris resulting from comminution of foraminiferal shells. When the chalk is treated with acid there remains a small amount of insoluble matter consisting of clay, fine grains of quartz sand, minute pebbles not exceeding 5 millimeters in diameter, and a very few internal casts of the chambers of Foraminifera. Nearly all the foraminiferal shells have the chambers filled with calcite; a few have these cavities still empty; but in a small number of cases the chambers were filled with an opaque, insoluble mineral, probably silica deeply stained with iron oxide, that remains as perfect internal casts after the shell has been dissolved in acid. The amount and composition of the residuum varies with the purity of the chalk. In some samples it scarcely exceeds 1 per cent, in others it is equal to 10 per cent."

Chalk was probably deposited in deep, quiet water little affected by débris from the land. At present material of exactly similar type is being formed in the deeper portions of the North Atlantic and other oceanic basins.

Distribution of chalk and soft limestones.—Both the true chalks and the other soft limestones here considered are of comparatively recent geologic age, occurring only in Cretaceous or Tertiary rocks. There is also a certain geographic unity apparent, for both types occur only along the Atlantic and Gulf coasts and in the Western States. For detailed information regarding the distribution of these rocks reference should be made to the papers and reports listed on page 291. In the present place only a summary can be given covering the more important features of the subject.

The true chalks occur only in formations of Cretaceous age in certain Southern and Western States. The principal chalk deposits available for use in Portland-cement manufacture occur in three widely separated

areas occupying respectively (*a*) parts of central Alabama and northeastern Mississippi, (*b*) southwestern Arkansas and central Texas, and (*c*) parts of Iowa, Nebraska, North and South Dakota, Colorado, and other States of the Great Plains region. Though the chalk is in all these areas of approximately the same age and character, the formations containing it have been given different names—i.e., the Selma chalk, in Alabama and Mississippi; the Whitecliffs chalk, in Arkansas; the Austin chalk, in Texas; and the Niobrara chalk, in the Great Plains region.

In addition to the true chalks, soft limestones of Tertiary age occur in all the Atlantic and Gulf Coast States from Virginia to Mississippi inclusive, as well as in California. These are the materials commonly described as "marls" in the older geological reports, though they are in no way related to the fresh-water marls now so largely used in Portland-cement manufacture, discussed in Chapter XXIII.

Physical Properties.—When dry, the chalks and soft limestones are commonly considerably lighter than the hard limestones. As noted on a previous page, the chalky limestones may run as low in specific gravity as 1.85 corresponding to a weight of about 110 pounds per cubic foot, while the hard, compact limestones in common use range in specific gravity from 2.3 to 2.9, corresponding approximately to a range in weight of from 140 to 185 pounds per cubic foot.

The low weight above quoted is, however, exceptional, and the soft limestones may be expected to range between 125 and 150 pounds per cubic foot when dry. They are usually very porous, however, and but brief exposure to water will increase their weight and moisture content remarkably. This, indeed, is their single defect from the point of view of the cement manufacturer, for during a rainy season or with a badly drained quarry he may have to handle a material carrying 15 or 20 per cent of moisture.

Otherwise they are admirable cement materials, being soft and easily quarried and ground.

Composition of chalks and soft limestones used in cement-plants.—In composition the chalks and other soft limestones vary from a rather pure lime carbonate low in both magnesia and clayey matter to an impure clayey limestone of about the composition of the Lehigh district cement rock. Magnesium carbonate is rarely present in quantities of over 2 or 3 per cent, but alkalies, sulphur, and phosphoric acid may occur in sufficient percentages to require careful considerations.

Examining chalk deposits.—The chalk deposits of most of the States have been carefully mapped by geological surveys, and much

time will be saved by procuring and studying the proper reports. These will give general data on the distribution and character of the chalk formations.

TABLE 145.

ANALYSES OF PURE CHALKS USED IN AMERICAN CEMENT-PLANTS.

	1.	2.	3.	4.	5.	6.	7.	8.
Silica (SiO_2)	5.33	4.42	6.09	3.83	4.14	2.15	5.77	2.22
Alumina (Al_2O_3)	3.03	2.21	3.52	2.31	1.81	2.72	2.14	0.92
Iron oxide (Fe_2O_3)		1.03	1.20		2.72			0.18
Lime (CaO)	50.53	53.36	49.24	52.16	51.00	52.48	50.45	54.08
Magnesia (MgO)	0.55	n. d.	n. d.	0.14	tr.	n. d.	0.28	0.10
Alkalies (K_2O,Na_2O)	n. d.	n. d.	n. d.	.....	tr.	n. d.	n. d.	n. d.
Sulphur trioxide (SO_3)	n. d.	n. d.	n. d.	0.20	0.50	n. d.	n. d.	
Carbon dioxide (CO_2)	50.30	n. d.	n. d.	41.64	39.99	n. d.	40.00	42.50
Water	n. d.	n. d.	n. d.		n. d.	n. d.	n. d.	

1. Whitecliffs P. C. Co., Whitecliffs, Ark. 18th Ann. Rep., U. S. Geol. Survey, pt. 5, p. 1174.
2-3. " " " " Trans. Amer. Institute Mining Engrs., vol. 21.
4. Western P. C. Co., Yankton, S. D. C. B. McVay, analyst.
5. " " " " Mineral Industry, vol. 1, p. 52.
6. " " " " " vol. 6, p. 97.
7. Alamo Cement Works, San Antonio, Texas. 22d Ann. Rep. U. S. Geol. Survey, pt. 3, p. 737.
8. Almendares P. C. Co., Marinao, Cuba. Engineering Record, vol. 49, p. 36.

TABLE 146.

ANALYSES OF CLAYEY CHALKS USED IN AMERICAN CEMENT-PLANTS

Silica (SiO_2)	9.88	7.64	12.13	13.32
Alumina (Al_2O_3)	6.20	7.62	4.17	8.74
Iron oxide (Fe_2O_3)			3.28	
Lime (CaO)	43.19	45.20	42.04	41.41
Magnesia (MgO)	0.52	0.59	0.44	0.67
Sulphur trioxide (SO_3)	n. d.	1.62	n. d.	0.27
Carbon dioxide (CO_2)	34.49	36.06	33.51	33.26
Water	5.72	1.36	n. d.	n. d.

In examining chalk deposits it is well to recollect that they are always found in thick and almost horizontal beds. Stream ravines usually give good natural sections, which will serve to give a preliminary idea of the character of the rock. In securing samples, the earth-auger gives satisfactory results in most chalk deposits, because the material is usually soft enough to be penetrated readily by this tool.

The principal impurities to be guarded against are nodules of pyrite and grains of sand, both of which are very common in many American chalk deposits.

List of references on chalks and soft limestones.—The following papers deal largely with the chalky limestones of the United States.

For convenience of reference those which consider chiefly the origin and structure of chalk are marked *A*; those which describe its distribution in certain States or areas are marked *B*.

B. Branner, J. C. The cement materials of southwest Arkansas. Trans. Am. Inst. Min. Engrs., vol. 27, pp. 42–63. 1898.

A. Calvin, S. The Niobrara chalk. Proc. Amer. Assoc. Adv. Sci., vol. 43, pp. 197–217. 1895.

A. Calvin, S. Composition and origin of Iowa chalk. Reports Iowa Geological Survey, vol. 3, pp. 211–236. 1895.

A. Dawson, G. M. Note on the occurrence of Foraminifera, etc., in the Cretaceous rocks of Manitoba. Canadian Naturalist, vol. 7, No. 5. 1874.

B. Eckel, E. C. Cement materials and cement industries of the United States. Bulletin 243, U. S. Geological Survey. 1905.

B. Hill, R. T. A brief description of the Cretaceous rocks of Texas and their economic value. 1st Ann. Report Texas Geological Survey, pp. 103–144. 1890.

A. B. Hill, R. T. Neozoic geology of southwestern Arkansas. Ann. Rep. Arkansas Geol. Survey for 1888, vol. 2.

A. Hill, R. T. The foraminiferal origin of certain Cretaceous limestones. American Geologist, Sept., 1889.

B. Smith, E. A. Report on the geology of the Coastal Plain of Alabama. Report Alabama Geological Survey, 759 pp. 1894.

B. Smith, E. A. Alabama's resources for the manufacture of Portland cement. Proc. Ala. Industrial and Scientific Society, vol. 5, pp. 44–51. 1895.

B. Smith, E. A. The cement resources of central and southern Alabama. Senate Document No. 19, 58th Congress, 1st session. 1903.

B. Smith, E. A. Cement resources of Alabama. Bulletin 225, U. S. Geological Survey, pp. 424–447. 1904.

B. Smith, E. A. Cement resources of Alabama. Bulletin 8, Alabama Geological Survey. 12mo, 93 pp. 1904.

B. Taff, J. A. Chalk of southwestern Arkansas, with notes on its adaptability to the manufacture of hydraulic cement. 22d Ann. Rep. U. S. Geol. Survey, pt. 3, pp. 687–742. 1902.

A. Williston, S. W. Chalk from the Niobrara Cretaceous of Kansas. Science, vol. 16, p. 294. 1890.

A. Williston, S. W. On the structure of the Kansas chalk. Trans. Kansas Acad. Sci., vol. 12, p. 100. 1890.

CHAPTER XXII

ARGILLACEOUS LIMESTONE: CEMENT ROCK.

THE term "cement rock" is here used to include all the very clayey limestones carrying from 50 to 80 per cent of lime carbonate, with correspondingly high percentages of argillaceous matter, and less than 8 per cent of magnesium carbonate. It is evident that an argillaceous limestone low in magnesia, and containing approximately 75 to 77 per cent of lime carbonate and 20 per cent or so of clayey materials (silica, alumina, and iron oxide) would be the ideal material for use in the manufacture of Portland cement; for a rock of this composition would contain within itself, mixed in the proper proportions, all the ingredients necessary for the manufacture of a good Portland. Such an ideal rock would require the addition of no other raw material, but when burnt alone would give a good cement.

This ideal cement material is, of course, never realized in practice, but certain deposits of clayey limestone approach it very closely in composition. A limestone carrying 70 or 80 per cent of lime carbonate and 20 to 30 per cent clayey matter will require the addition either of pure limestone or of clay in order to bring it to the desired composition for a Portland-cement mixture. But it will be, of itself, so *near* to the correct composition that it will need but little of the extra raw material to make it absolutely perfect. Deposits of such "cement rocks" possess important technologic advantages, and have been sought for with great industry. Many such deposits of clayey limestones, low in magnesia, occur in various parts of the United States, but few of them are well located with regard to transportation routes, fuel supplies, and markets.

The most important of these argillaceous limestone, or "cement-rock," deposits is at present that which is so extensively utilized in Portland-cement manufacture in the "Lehigh district" of Pennsylvania and New Jersey, though similar "cement rocks" occur in many other States. As the Lehigh district still produces one quarter of the Portland cement manufactured in the United States, its raw materials will be described below in some detail, after which other areas of "cement rock" will be briefly noted.

Cement Rock of the Lehigh District, Pennsylvania-New Jersey.

The "Lehigh district" of the cement manufacturer has been so greatly extended in recent years that the name is now hardly applicable. Originally it included merely an area about 4 miles square, located along the Lehigh River partly in Lehigh County and partly in Northampton County, and containing the villages of Egypt, Coplay, Northampton, Whitehall, and Siegfried. The cement-plants which were early located here secured control of most of the cement-rock deposits in the vicinity, and plants of later establishment have therefore been forced to locate farther away from the original center of the district. At present the district includes parts of Berks, Lehigh, and Northampton Counties, Pa., and Warren County, N. J., reaching from near Reading, Pa., at the southwest, to a few miles north of Stewartsville, N. J., at the northeast. It forms an oblong area about 25 miles in length from southwest to northeast and about 4 miles in width. Within this area about twenty Portland-cement plants are now in operation, and the Portland cement produced in this relatively small district amounts to a quarter of the entire United States output.

Geology of the district.—Within the "Lehigh district" three geologic formations occur, all of which must be considered in attempting to account for the distribution of the cement materials used here. These three formations are, in descending order, the (1) Hudson shales, slates, and sandstones; (2) Trenton limestone (Lehigh cement rock); (3) Kittatinny limestone (magnesian). As all these rocks dip, in general, northwestward, the Hudson rocks occupy the northwestern portion of the district, while the cement rock and magnesian limestone outcrop in succession farther southeast.

Hudson shale.—This series includes very thick beds of dark-gray to black shales, with occasional thin beds of sandstone. In certain localities, as near Slatington and Bangor, Pa., and Newton, N. J., these shales have been so altered by pressure as to become slates, the quarrying of which now supports a large roofing-slate industry.

The composition of the typical shales and slates of the Hudson formation is well shown by the following analyses (Table 147).

The geographic distribution of the Hudson shales and slates in the Lehigh district can be indicated only approximately without the presentation of a geologic map of the area. They cover practically all of Northampton, Lehigh, and Berks counties north of a line passing through Martins Creek, Nazareth, Bath, Whitehall, Ironton, Guthsville, Monterey, Kutztown, Molltown, and Leesport.

The rocks of the Lehigh district have a general dip to the northwest, though there are numerous local exceptions to this rule. The lowest beds of the Hudson series, therefore, are those which outcrop along the southern boundary of the formation, as above outlined. These lowest beds carry much more lime and less silica, alumina, and iron than the higher beds whose analyses are given in Table 147. The lowest beds form a natural transition into the underlying cement rock.

TABLE 147.

ANALYSES OF HUDSON SHALE AND SLATE IN PENNSYLVANIA AND NEW JERSEY.

	1.	2.	3.	4.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Silica (SiO_2)	68.62	68.00	56.60	*76.22
Alumina (Al_2O_3)	12.68	14.40	21.00	13.05
Iron oxide (Fe_2O_3)	4.20	5.40	5.65	
Lime (CaO)	1.31	2.68	3.42	2.67
Magnesia (MgO)	1.80	1.51	2.30	0.93
Alkalies	3.73	0.11	0.50	n. d.
Carbon dioxide (CO_2)	2.99	2.30	2.20	n. d.
Water (H_2O)	4.47	2.70	3.00	n. d.

* Insoluble.

1. East Bangor, Pa. 20th Ann. Rep. U. S. Geol. Survey, pt. 6, p. 436.
2. 1 mile northwest of Colemanville, N. J. Geology New Jersey, 1868, p. 136.
3. Delaware Water Gap, N. J. Geology New Jersey, 1868, p. 136.
4. Lafayette, N. J. Rept. New Jersey State Geol. for 1900, p. 74.

Trenton limestone.—The Lehigh cement rocks, which are equivalent in age to the Trenton limestone beds of New York, are made up of a series of argillaceous limestones. The formation appears to vary in thickness from 150 feet in New Jersey to 250 feet or even more at Nazareth and on the Lehigh River. Its upper beds near the contact with the overlying Hudson shales are very shaly or slaty black limestones carrying approximately 50 to 60 per cent of lime carbonate and 40 to 50 per cent of silica, alumina, iron, etc. Lower in the formation the percentage of lime steadily increases, while that of clayey material decreases correspondingly, until near the base of the formation the rock may carry from 85 to 95 per cent of lime carbonate with only 5 to 15 per cent of impurities. This change in chemical composition is accompanied by a change in the appearance and physical character of the rock, which gradually loses its slaty fracture and blackish color as the percentage of lime increases, until near the base of the formation it is often a fairly massively bedded dark-gray limestone. Even so, it can usually be readily distinguished from the magnesian Kittatinny limestone, described below, for the cement rock is always darker than the magnesian limestone and

contains none of the chert beds which are so common in the magnesian rock.

The Lehigh cement rock is never nearly so high in magnesia as is the underlying Kittatinny limestone. It does, however, carry considerable magnesia (as compared with other Portland-cement materials) throughout its entire thickness, and few analyses will show less than 4 to 6 per cent of magnesium carbonate. The following series of analyses is fairly representative of the lower, middle, and upper beds of the formation. The specimens from the upper beds, near the Hudson shales, show considerably less lime and more clayey matter than those from the lower parts of the formation.

TABLE 148.

ANALYSES OF TRENTON LIMESTONE (LEHIGH CEMENT ROCK)

	1.	2.	3.	4.	5.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Silica (SiO_2)	1.86	5.03	8.38	11.90	11.71
Alumina (Al_2O_3)	.60	2.06	4.03	4.42	4.36
Iron oxide (Fe_2O_3)	.51	1.23	1.32	1.70	1.62
Lime (CaO)	53.64	49.73	45.45	44.18	43.47
Magnesia (MgO)	.81	1.02	1.34	1.18	1.82
Carbon dioxide (CO_2)	43.03	40.19	37.18	36.01	36.15

	6.	7.	8.	9.	10.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Silica (SiO_2)	11.11	17.04	22.71	19.53	24.45
Alumina (Al_2O_3)	4.40	6.90	5.84	6.03	5.68
Iron oxide (Fe_2O_3)	1.91	2.13	2.13	1.70	1.57
Lime (CaO)	42.51	37.53	36.50	35.71	35.00
Magnesia (MgO)	2.89	2.17	1.69	3.33	2.21
Carbon dioxide (CO_2)	36.57	32.88	30.52	32.73	29.89

Ann. Rept. New Jersey State Geologist for 1900, p. 95.

The specimens whose analyses are given above were mostly from the vicinity of Belvidere, N. J., and though representative in other respects, seem to have been rather lower in magnesia than the usual run of the Trenton limestone in the Lehigh district.

Kittatinny magnesian limestone.—Underlying the cement-rock series is a very thick formation consisting of light-gray to light-blue massive-bedded limestone, with frequent beds of chert. These limestones are predominantly highly magnesian, though occasionally beds of pure non-magnesian limestone will be found in the series. The magnesian beds are, of course, valueless for Portland-cement manufacture, but

the pure limestone-beds furnish part of the limestone used in the Lehigh district for addition to the cement rock. An excellent example of this is furnished by the quarry near the east bank of Lehigh River, just above Catasauqua. In this quarry most of the beds are highly magnesian, and are therefore useful only for road metal and flux; but a few pure limestone beds occur, and the material from these low-magnesia beds is shipped to a neighboring cement-mill.

Numerous analyses of the highly magnesian limestones are available, from which a few typical results have been selected for insertion here. Analyses of the purer limestone, used to add to the cement rock, will be found in the table on page 298.

TABLE 149.

ANALYSES OF KITTATINNY MAGNESIAN LIMESTONE.*

	1.	2.	3.	4.	5.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Silica (SiO_2)	9.9	9.9	8.8	5.5	9.8
Alumina (Al_2O_3) / Iron oxide (Fe_2O_3)	1.7	1.7	0.8	1.3	3.7
Lime (CaO)	27.6	28.5	29.4	28.2	26.4
Magnesia (MgO)	17.9	17.3	17.8	20.2	15.1
Carbon dioxide (CO_2)	41.9	41.5	42.8	44.3	45.0

	6.	7.	8.	9.	10.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Silica (SiO_2)	4.9	2.0	8.0	4.1	16.9
Alumina (Al_2O_3) / Iron oxide (Fe_2O_3)	6.5	8.4	5.3	1.6	1.0
Lime (CaO)	27.3	32.4	26.3	30.3	28.3
Magnesia (MgO)	14.6	15.5	17.4	18.3	15.3
Carbon dioxide (CO_2)	44.8	42.5	41.1	44.1	38.9

* From various reports of the New Jersey Geological Survey.

1. Chandlers Island, Sussex County, N. J.
2. Sparta, Sussex County, N. J.
3. Asbury, Warren County, N. J.
4. Oxford Furnace, Sussex County, N. J.
5, 6. Clinton, Hunterdon County, N. J.
7. Pottersville, Somerset County, N. J.
8, 9. Peapack, N. J.
10. Annandale, N. J.

While all of the above analyses are from New Jersey localities, the magnesian limestone of the rest of the Lehigh district would give closely similar results.

Throughout most of the Lehigh district the practice is to mix a small amount of pure limestone with a relatively large amount of the " cement rock " or argillaceous limestone, in order to bring the lime carbonate content up to the percentage proper for a Portland-cement mixture. As above noted, all of the " cement rock " is derived from the

middle part of the Trenton formation, where the beds will run from 60 to 70 per cent of lime carbonate. The pure limestone which is required to bring this material up to the necessary percentage of lime carbonate (75 per cent or so) is obtained either from the lower portion of the Trenton itself or from certain low-magnesia beds occurring in the Kittatinny formation.

In the plants located near Bath and Nazareth, however, the practice has been slightly different. In this particular area the cement-rock quarries usually show rock carrying from 75 to 80 per cent of lime carbonate. The mills in this vicinity, therefore, require practically no pure limestone, as the quarry rock itself is sufficiently high in lime carbonate for the purpose. Indeed, it is at times necessary for these plants to add clay or slate, instead of limestone, to their cement rock, in order to reduce its content of lime carbonate to the required figure. In general, however, it may be said that Lehigh practice is to mix a low-carbonate cement rock with a relatively small amount of pure limestone, and analyses of both these materials, as used at various plants in the district, are given below in Tables 150 and 151.

Character and composition of the cement rock.—The cement rock is a dark-gray to black, slaty limestone, breaking with an even fracture into flat pieces, which usually have smooth, glistening surfaces. As the percentage of lime carbonate in the rock increases—i.e., as the lower beds of the formation are reached—the color becomes a somewhat lighter gray and the surfaces of the fragments lose their slaty appearance.

The range in composition of the cement rock as used at various plants is well shown in the first eight columns of the above table. The nearer the material from any given quarry or part of a quarry approaches the proper Portland-cement composition (say 75 to 77 per cent lime carbonate) the less addition of pure limestone will be necessary. In by far the greater part of the district, as above noted, the cement rock is apt to run about 65 to 70 per cent of lime carbonate, therefore requiring the addition of a proportionate amount of limestone. Most of the quarries near Bath and Nazareth, however, have been opened on beds of cement rock running considerably higher in lime carbonate and occasionally running so high (80 per cent, etc.) as to require the addition of shale or clay rather than of pure limestone.

Character and composition of the pure limestones.—The pure limestones added to the cement rock are commonly gray and break into rather cubical fragments. The fracture surfaces show a finely granular structure quite distinct in appearance from the slaty cement rock.

In composition the limestones commonly used will carry from 90 to 96 per cent of lime carbonate, with rather less magnesium carbonate than is found in the cement rock. All of the cement-plants own and operate their own cement-rock quarries, but most of them are compelled to buy the pure limestone. When this is the case only very pure grades of limestone are purchased, but when a cement-plant owns its limestone quarry material running as low as 85 per cent of lime carbonate is often used.

TABLE 150.

ANALYSES OF HIGHLY CLAYEY LIMESTONES: "CEMENT ROCK."

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Carbon Dioxide (CO_2).	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$.	Cementation Index.
1	18.30	6.11	1.85	36.38	2.13	28.96	2.29	1.51
2	15.97	7.53	2.24	34.34	3.93	32.80		
3	17.32	9.11		38.59	2.05	32.55		
4	19.62	5.68		39.08	2.35	33.25		
5	16.77	6.50		41.37	n. d.	n. d.		
6	15.73	7.92		39.62	1.81	33.08	....	1.23
7	19.06	4.44	1.14	38.77	2.02	32.66		
8	22.22	7.24	0.92	35.53	2.19	30.29	2.72	
9	19.08	7.92		37.56	1.95	31.62		
10	14.20	6.14		41.51	1.56	34.47		
11	14.52	6.52		41.17	2.25	34.79		
12	15.05	9.02	1.27	39.26	1.90	32.90	1.46	
13	15.20	8.80		38.70	1.47	31.99		

TABLE 151.

ANALYSES OF PURE LIMESTONES USED FOR MIXING WITH CEMENT ROCK.

Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Carbon Dioxide (CO_2).
3.64	0.61		52.93	n. d.	n. d.
5.56	2.40		50.47	1.00	40.73
3.02	1.90		51.55	1.46	42.08
1.98	0.70		53.31	0.97	42.94
2.14	1.46		52.84	1.05	42.64
4.50	0.82		51.50	0.66	41.19
3.40	0.70		52.53	0.61	41.94
1.02	0.48		54.60	0.53	43.47
0.08	0.40		54.90	0.61	43.80
6.1	3.5		47.21	2.35	39.64

Quarry practice.—In most of the cement-rock quarries of the Lehigh district the rock dips from 15° to 25°, usually to the northwest. At a few quarries, particularly in New Jersey, the dip is much steeper. The quarries are opened preferably on a side-hill, and the overlying stripping, which consists of soil and weathered rock, is removed by scrapers or shoveling. The quarry of the Lawrence Cement Company has been extended in its lower levels so as to give a tunnel through which the material is hoisted to the mill. Several other quarries have been carried straight down, until now they are narrow and deep pits.

FIG. 67.—Tunnel, Lawrence Cement Co., Siegfried, Pa.

In quarries opened on a side-hill, so as to have a long and rather low working-face and a floor at the natural ground level, the rock is commonly blasted down in benches, sledged to convenient size for handling and crushing, and carried by horse carts to a point in the quarry some distance from the face where the material can be dumped into cars, which are hauled by cable to the mill. Occasionally the material is loaded at the face into small cars running on temporary tracks. The loaded cars are then drawn by horses or pushed by men

to a turntable, where they are connected to the cable and hauled to the mill. While these methods seem clumsy at first sight, they are capable of little improvement. The amount of rock used every day in a large mill necessitates very heavy blasting, and this prevents permanent tracks and cableways from being laid near to the working-face.

At several quarries the loading into the cars or carts is accomplished by means of steam-shovels. The cement rock seems to be well adapted

FIG. 68.—Open cut in cement rock.

for handling by steam-shovels, but even then much sledging is necessary and the blasting operations are interfered with.

These difficulties, which formerly limited the employment of steam shovels and of permanent track are now reduced or eliminated by the practice of deep-hole blasting, throwing down a large supply of rock at one point or along one face of the quarry. Economical quarry operations have gained greatly by this system, which permits cheap and steady handling of the blasted rock, unattainable under older methods.

Cement production of the district.—The importance of these Lehigh district cement-rock deposits is well brought out by Table 152.

Probable extension of the industry.—As noted in the earlier portion of this chapter, the cement deposits have been developed only from near Reading, Pa., to a few miles west of Stewartsville, N. J. Most of the readily accessible cement land between these points has been taken up by the cement companies or is being held at impossible prices by the owners. Under these circumstances it seems probable that few additional plants can be profitably established in the district now developed, and that the growth of the industry here will be brought about by extending the district. A few notes on the distribution of the same cement-beds in adjoining areas may therefore be of interest to those desiring to engage in the manufacture of Portland cement from materials of the Lehigh district type.

TABLE 152.

PORTLAND-CEMENT PRODUCTION OF THE LEHIGH DISTRICT, 1890–1920.

Year.	Lehigh District (Barrels).	United States (Barrels).	Percentage Made in Lehigh District.	Year.	Lehigh District (Barrels).	United States (Barrels).	Percentage Made in Lehigh District.
1890	201,000	335,500	60.0	1905	17,368,687	35,246,812	49.3
1891	248,500	454,813	54.7	1906	22,784,613	46,453,424	49.0
1892	280,840	547,440	51.3	1907	24,417,686	48,785,390	50.0
1893	265,317	590,652	44.9	1908	20,200,387	51,072,612	39.6
1894	485,329	798,757	60.8	1909	24,246,706	64,991,431	37.3
1895	634,276	990,324	64.0	1910	26,315,359	76,549,951	34.4
1896	1,048,154	1,543,023	68.1	1911	25,972,108	78,528,637	33.1
1897	2,002,059	2,677,775	74.8	1912	24,762,083	82,438,096	30.0
1898	2,674,304	3,692,284	72.4	1913	27,139,601	92,097,131	29.5
1899	4,110,132	5,652,266	72.7	1914	24,614,933	88,230,170	27.9
1900	6,153,629	8,482,020	72.6	1915	24,876,442	85,914,907	29.0
1901	8,595,340	12,711,225	67.7	1916	24,105,381	91,521,198	26.3
1902	10,829,922	17,230,644	62.8	1917	24,423,507	92,814,202	26.3
1903	12,324,922	22,342,973	55.2	1918	19,701,820	71,081,663	27.7
1904	14,211,039	26,505,881	53.7	1920	25,417,804	100,023,245	25.4

Northeast of Stewartsville, N. J., the cement-beds outcrop at frequent intervals in the Kittatinny Valley all the way across New Jersey and a few miles into Orange County, N. Y. The exact locations of these deposits, with numerous analyses of the cement rocks, are given in the Annual Report of the State Geologist of New Jersey for 1900, pages 41–95. Many detailed maps in this report show the outcrops very precisely.

Southwestward from Reading the Trenton beds outcrop in a belt crossing Lebanon, Cumberland, and Franklin counties, Pa., passing near the towns of Lebanon, Harrisburg, Carlisle, and Chambersburg. In Maryland the Trenton rocks occur in Washington County, while in

West Virginia and Virginia they are extensively developed. The distribution of these rocks in Virginia is discussed in the papers by Messrs. Bassler and Catlett, cited in the list on page 303.

Throughout this southern extension of the Lehigh rocks, the Trenton is not everywhere an argillaceous limestone, but it is frequently so, and it is always very low in magnesium carbonate. It is therefore probably safe to say that in southern Pennsylvania, Maryland, West Virginia, and Virginia the Trenton rocks are everywhere good Portland-cement materials, though in some cases they will require pure limestone, and in other places clay, to bring them to proper composition.

Cement Rocks in Other States.

Limestones sufficiently clayey to be called " cement rocks " are not by any means confined to the Lehigh district, nor even to the immediate vicinity of the fortunate area. As noted in the last chapter, cement rock exactly similar to that used in the Lehigh district occurs in other parts of Pennsylvania, in Maryland, and the Virginias. Similar clayey limestones occur southward, along the Appalachian Valley, through Tennessee and northern Georgia. In all this range, however, they have never been used as Portland-cement materials, though a natural-cement plant was erected a few years ago at Rossville, Ga., a few miles south of Chattanooga, to utilize limestones closely similar to the Lehigh rock in composition.

The following analyses show the composition of " cement rocks " used at various Portland-cement plants in the Western States, together with that of the purer limestones used for mixing.

TABLE 153.

ANALYSES OF "CEMENT-ROCK" MATERIALS FROM THE WESTERN UNITED STATES.

	Utah.		California.		Colorado.	
	Cement Rock.	Limestone.	Cement Rock.	Limestone.	Cement Rock.	Limestone.
Silica (SiO_2)	21.2	6.8	20.06	7.12	14.20	
Alumina (Al_2O_3)	8.0	3.0	10.07	2.36	5.21	
Iron oxide (Fe_2O_3)	.....	.....	3.39	1.16	1.73	
Lime carbonate ($CaCO_3$)	62.08	89.8	63.40	87.70	75.10	88.0
Magnesium carbonate ($MgCO_3$)	3.8	0.76	1.54	0.84	1.10	

In addition to the " cement rocks " noted in this chapter, it is necessary to call attention to the fact that many of the chalky limestones

discussed in the preceding chapter are sufficiently argillaceous to be classed as "cement rocks." Because of their softness, however, all these chalky limestones will be described together.

List of references on "cement rock."

Bassler, P. S. Cement materials of the Valley of Virginia. Bulletin 260, U. S. Geol. Survey, pp. 531–544. 1905.

Catlett, C. Cement resources of the Valley of Virginia. Bulletin 225, U. S. Geol. Survey, pp. 457–461. 1904.

Eckel, E. C. Cement-rock deposits of the Lehigh district of Pennsylvania and New Jersey. Bulletin 225, U. S. Geol. Survey, pp. 448–456. 1904.

Eckel, E. C. Cement materials and cement industries of the United States. Bulletin 243, U. S. Geol. Survey, pp. 279–293. 1905.

Kümmel, H. B. Report on the Portland-cement industry in New Jersey. Ann. Rep. N. J. State Geologist for 1900, pp. 9–101.

Peck, F. B. The cement-belt of Lehigh and Northampton counties, Pennsylvania. Mines and Minerals, vol. 25, pp. 53–57. 1904.

CHAPTER XXIII

FRESH-WATER MARLS.

MARLS, in the sense in which the term is used in the Portland-cement industry, are fine-grained, friable limestones which have been deposited in the basins of existing or extinct lakes. So far as chemical composition is concerned, marls are practically pure limestones, being usually composed almost entirely of calcium carbonate. Physically, however, they differ greatly from the hard, compact rocks to which the term limestone is more commonly applied, for the marls are granular, loose, non-coherent deposits. These curious physical characters of marls, as compared with ordinary limestones, are due to the peculiar conditions under which the former have been deposited. Samples of marl from different localities will on comparison be found to exhibit considerable variations, and these arise in large part from differences in local conditions during deposition.

As explained on a later page, differences of opinion exist as to the exact cause of the formation of marl deposits. The points in controversy are of no particular practical importance, and may be disregarded in the present brief statement of facts. It may safely be said that marls are deposited in lakes by spring or stream waters carrying lime carbonate in solution. The actual deposition of the marl is in part due to purely physical and chemical causes, and in part to the direct or indirect action of animal or vegetable life. The result in any case is that a calcareous deposit forms along the sides and over the bottom of the lake, this deposit consisting of lime carbonate, mostly in a finely granular form, interspersed with shells and shell fragments.

Various uses of the term "marl."—A warning to the reader concerning other uses of the term "marl" may profitably be introduced here. The meaning above given is that in which the term marl is commonly used in the cement industry at the present day. But in geological and agricultural reports, particularly in those issued before the Portland-cement industry became prominent in this country, the term marl has been used to cover several very different substances. The following three uses of the term will be found particularly common, and must

be guarded against when such reports are being examined in search for descriptions of deposits of cement materials.

1. In early days the terms "marls" and "marlytes" were used to describe deposits of calcareous shales—and often these terms were extended to cover shales which were not particularly calcareous. This use of the term will be found in many of the earlier geological reports issued by New York, Ohio, and other interior States.

2. In New Jersey and the States southward bordering on the Atlantic and Gulf of Mexico the term marl is commonly applied to deposits of soft chalky or unconsolidated limestone often containing considerable clayey and phosphatic matter. These limestones are of marine origin and not related to the fresh-water marl deposits which are the subject of the present chapter.

3. In the same States, but particularly in New Jersey and Virginia, large deposits of the so-called "green-sand marls" occur. This material is in no way related to the true marls (which are essentially lime carbonates), but consists largely of the iron silicate called glauconite, or green sand, with very small percentages of clayey, calcareous, and phosphatic matter.

The three early uses of the term "marl" above noted all agree in that they apply to deposits of marine origin, while the marls of the cement manufacturer are purely fresh-water deposits.

Occurrence of marl deposits.—Fresh-water marls occur in more or less lenticular or basin-shaped deposits of relatively small size. Their form and local character are both due to the fact that the marls were formed by deposition in lake basins. In many cases these lakes still contain water, and in some instances marl deposition is now in progress. In other cases, however, the lake has entirely disappeared, and the marl-bed now occurs in a swamp or marsh covered with peat or muck.

The disappearance of a lake in this fashion must be regarded as part of a very natural and almost invariable cycle of events. The existence of a lake at any point along a drainage system is to be considered a somewhat unnatural and temporary condition, and one which will be removed by natural causes as soon as possible. In the glaciated portion of the United States many lakes were formed at the close of the Glacial period. These lakes were due in some cases to the fact that deposits of sand and clay laid down by the glaciers had filled old valleys and dammed the streams occupying such valleys. In other cases the lake basins were formed by the irregular distribution of these glacial deposits, leaving hollows and depressions which subsequently became filled with water. In either case a lake or pond was formed, and imme-

diately a series of natural forces were set in operation which tended to remove this lake. Of the two common methods of lake disappearance, one has but little to do with our present subject, but the other is closely connected with the history of marl deposition. The first method is the gradual deepening of the outlet by the action of its own current, resulting in the draining of the lake. The second is the filling up of the lake basin by deposits of sand, clay, marl, muck, and peat.

Origin of marl deposits.—The exact cause of the formation of marl deposits has been the subject of much investigation and discussion, particularly in the past few years, since these deposits have become of so great economic importance. For details concerning this discussion, reference should be made to the papers listed on page 316–317, especially to those by Davis and Blatchley. In the present place only a summary of the main facts—and theories—in regard to the formation of marl deposits will be given.

Marl deposits in their present form and position are due directly or indirectly to glacial action, on which account these deposits occur almost exclusively in that portion of the country which was covered by ice during the Glacial epoch. The glaciers aided in the formation of marl deposits in two ways: first, by furnishing a large supply of finely ground calcareous material from which surface waters could take up lime carbonate in solution, and, second, by forming the lake basins in which these waters deposited their burden of lime carbonate as marl. The processes followed in the formation of marl deposits may be outlined with some confidence, though certain of the steps are still subject to discussion.

Rain-water, though theoretically pure before approaching the earth's surface, takes up a considerable percentage of carbon dioxide in passing through the atmosphere. When it reaches the surface, therefore, such rain-water is in reality a very dilute form of carbonic acid (H_2CO_3), and as such is capable of attacking limestone, taking the lime carbonate ($CaCO_3$) into solution in the form of calcium bicarbonate ($CaH_2(CO_3)_2$). Practically all natural water, including the percolating ground-water as well as spring and stream water, is therefore able to change itself with lime carbonate if some source of that compound presents itself. In the present marl districts such a source is not far to seek, for from New York to Michigan limestones cover a large proportion of the surface. The glaciers during their advance over this area ground up vast quantities of the surface rocks, leaving the pulverized débris in the form of deposits of limey gravels and limey clays.

Surface waters running through such areas, or underground waters

percolating through beds of limestone or coarse limey clays, will, if charged with carbon dioxide, dissolve and carry off lime carbonate, the exact amount so dissolved being determined by the percentage of CO_2 contained in the water, its temperature, etc. The tendency is for every water to charge itself with its maximum possible amount of calcium bicarbonate, and until it is so charged it will continue to attack and dissolve limestones which it encounters in its course.

When the water is almost or quite saturated with calcium bicarbonate, any increase in temperature or decrease in pressure will cause the deposition of lime carbonate. Reactions of this type have been appealed to as explanations of the formation of marl deposits through the warming or loss of pressure which occurs when spring or stream water enters a lake. A recent statement * of this theory is as follows:

" This spring-water as it enters the lake is always colder than the waters of the lake itself. The bicarbonate of lime is more soluble in cold water than in warm and a *part* of the dissolved material is therefore precipitated in the form of a fine powder soon after the cold stream enters the warmer, still water of the lake. Such precipitation of calcium carbonate from cold water as it becomes warm is seen every day in almost every household. The hard water heated in tea-kettles holds while cold a large quantity of bicarbonate of lime in solution. As it becomes warm, much, if not all of this falls and forms a coating of lime carbonate upon the bottom of the kettle.

" Again, if there is a large amount of carbon dioxide in the percolating waters the percentage of carbonate of lime held in solution will be increased in proportion. As the spring-water enters the lake and rises to the surface the pressure will be decreased and a part of the carbon dioxide will escape and so cause a precipitation of *another* part of the carbonate of lime according to the following formula:

" $CaH_2(CO_3)_2 - CO_2 = CaCO_3 + H_2O$."

In support of his belief that the formation of most marl deposits is due to the two causes above outlined, Blatchley urges that most, if not all, of the marl lakes examined in Indiana are fed by subterranean or subaqueous springs, even though they also have streams entering and leaving them, and that " the larger deposits of marl in the lakes are found in close proximity to these springs."

Davis, in studying the Michigan marls, came to the conclusion that the causes above noted would not of themselves account for the majority

* Blatchley, W. S. 25th Ann. Rep. Indiana Dept. Geology, p. 45.

of marl deposits. His studies * led him to believe that more important effects were due to the action of certain aquatic plants of low type, notably *Chara* (sonewort) and *Zonotrichia*, another alga. Plants of higher type are also influential in marl deposition, but to a less degree. Davis has summarized † his views as follows:

"All green plants, whether aquatic or terrestrial, take in the gas (carbon dioxide) through their leaves and stems and build the carbon atoms and part of the oxygen atoms of which the gas is composed into the new compounds of their own tissues, in the process releasing the remainder of the oxygen atoms. Admitting these facts, we have two possible general causes for the formation of the incrustation (of calcium carbonate) upon all aquatic plants. If the calcium and other salts are in excess in the water, and are held in solution by free carbon dioxide, then the more or less complete abstraction of that gas from the water in direct contact with plants causes precipitation of the (lime) salts upon the parts abstracting the gas, namely, the stems and leaves. But in water containing the salts, especially calcium bicarbonate, in amounts so small that they would not be precipitated if there were no free carbon dioxide present in the water at all, the precipitation may be considered a purely chemical problem, a solution of which may be looked for in the action, upon the bicarbonates, of the oxygen set free by the plants. Of these bicarbonates, calcium bicarbonate is the most abundant, and the reaction upon it may be taken as typical and expressed by the following chemical equation:

$$\underset{\text{Calcium bicarbonate}}{CaH_2(CO_3)_2} + \underset{\text{oxygen}}{O} = \underset{\text{calcium carbonate}}{CaCO_3} + \underset{\text{carbon dioxide}}{CO_2} + \underset{\text{water}}{H_2O} + \underset{\text{oxygen}}{O},$$

in which the calcium bicarbonate is converted into the normal (and very slightly soluble) carbonate by the oxygen liberated by the plants, and both carbon dioxide and oxygen are set free, the free oxygen possibly acting still further to precipitate calcium monocarbonate. It is probable that the plants actually do precipitate calcium carbonate in both these ways (i.e., by abstracting carbon dioxide from the water and by freeing oxygen), but in water containing relatively small amounts of calcium bicarbonate the latter would seem to be the probable method."

Professor Davis has further proven that *Chara* acts in still a third way, abstracting lime salts directly from the water as part of its life processes and depositing them in its tissues.

* See papers by Davis, cited in list on pp. 316–317.

† Vol. 8, pt. 3, Reports Michigan Geol. Survey, p. 69.

A further possible mode of derivation, which is admittedly the way in which *part* of all the marl deposits have originated, is through the direct action of molluscs. These animals are especially frequent in limey waters and have the power of abstracting lime salts from the water and utilizing the resulting lime carbonate in the formation of their shells. On the death of the animals their shells sink to the bottom and form an essential portion of any deposit which is in process of formation. In some marl-beds shells amount to an important percentage of the total, but in most cases they will probably constitute less than 5 per cent of the entire mass.

The facts so far stated may be summarized as follows: Spring or stream water, carrying lime carbonate in solution, deposits it in lakes in the form of marl, this deposition being caused by:

(*a*) Escape of carbon dioxide, owing to decrease in pressure;
(*b*) Supersaturation, owing to rise in temperature;
(*c*) Abstraction of carbon dioxide by plants;
(*d*) Freeing of oxygen by plants, resulting in formation of carbonates from bicarbonates;
(*e*) Direct abstraction and crystallization of lime salts by *Chara*.
(*f*) Abstraction of lime by molluscs and formation of shell deposits.

The formation of a given marl-bed may be due to the operation of any one of these causes, or the cooperation of two or more of them.

Geographic distribution of marl deposits.—The geographic distribution of marl deposits is intimately related to the geologic history of the region in which they occur. Marl-beds are, as indicated in the preceding section, the result of the filling of old lake basins. Lakes are not common except in those portions of the United States which were affected by glacial action, since lakes are in general due to the damming of streams by glacial material or to irregularities in deposition of such material. Workable marl deposits, therefore, are almost exclusively confined to those portions of the United States and Canada lying north of the former southern limit of the glaciers.

Marl-beds are found in the New England States, where, however, they are seldom of important size, and in New York, large beds occurring in the central and western portions of that State. Deposits are frequent and important in Michigan, and in the northern portion of Ohio, Indiana, and Illinois. Marl-beds occur in Iowa, Wisconsin, and Minnesota, but have not been as yet exploited for cement-manufacture. Extensive

marl-beds also occur in Ontario, Quebec, and other Canadian provinces.

Physical characters of marl.—Marl as found in existing lakes may contain as high as 50 per cent of water, while even the dry marl-beds occurring in swamps or marshes will carry 15 to 25 per cent of moisture. This moisture, together with the fine granular character of the marl itself, gives it a sticky, putty-like character. In color pure marl is white, but it usually contains so much organic matter as to give even the better samples a grayish or yellowish tint, while the more impure marls may be very dark gray in color.

Marl usually contains very little sand or grit, though some of its shells and lime carbonate particles may give it a gritty feeling when examined. Such shells, etc., can, however, be usually crushed between the fingers, which will serve to distinguish them in the field from sand grains. Though as sticky as clay, marl is markedly lighter in weight, owing to the high percentage of moisture which it contains.

The natural fineness of marl is a matter which is of direct interest to the Portland-cement manufacturer, because of its effect on the cost of grinding the raw material. Marls differ quite widely in this regard, some being fine-grained throughout, while others contain considerable percentages of coarse material, including shells, etc.

The sieving tests tabulated below * were carried out by Prof. Davis on samples of marl from three Michigan localities, and serve to show the differences in fineness above noted.

TABLE 154.

FINENESS OF CRUDE MARL. (DAVIS.)

	1.	2.	3.
	Per Cent.	Per Cent.	Per Cent.
Residue on 20-mesh sieve	32.25	31.52	0.36
" " 40- " "	6.06	14.48	3.53
" " 60- " "	7.58	12.76	6.51
" " 80- " "	2.90	2.56	3.34
" " 100- " "	4.81	6.74	6.44
Passing 100- " "	46.40	31.94	79.82

1. Cedar Lake.
2. Littlefield Lake.
3. Michigan P. C. Co., Coldwater.

The weight of the marl is also a matter of economic interest. A wet marl, as dredged from a lake bottom carrying from 50 to 60 per cent of water, may average about 2000 pounds per cubic yard, so that a cubic

* Vol. 8, pt. 3, Reports Michigan Geol. Survey, pp. 74–77.

yard of such material would contain only about 800 to 1000 pounds dry marl. A dry marl taken from a well-drained marsh or swamp may run as low as 20 per cent of water. Such a marl would then weigh about 2600 pounds per cubic yard, and a cubic yard would contain about a ton of pure marl.

In dealing with the wet marls a cement-plant may produce from one and a half to three barrels of cement from each cubic yard of marl, while a marsh marl might yield four barrels cement per cubic yard. In estimating the life of a lake marl deposit it will be safest to assume that each cubic yard of marl in place will produce only two barrels of cement.

Chemical composition of marl.—Marl itself, being a chemical deposit, is almost a pure carbonate of lime. During and after its deposition, however, foreign matter of various kinds is apt to get mixed in with the marl, the principal impurities thus introduced being fine sand, clayey matter, and organic material. Of these the most important, from the cement manufacturer's point of view, is the organic matter.

Sand is rarely present in sufficient amount to render the marl unserviceable, and of the 2 or 3 per cent of sand shown by most marls some is fine enough to pass a 150-mesh sieve and will therefore enter into combination in the kiln. The clay present in marls is principally objectionable because of its tendency to increase the percentage of magnesia and sulphur trioxide.

Organic matter burns out in the kiln and might therefore be regarded as a harmless impurity. But a high percentage of it in a marl is in reality very objectionable, both negatively, because it lowers the percentage of lime carbonate in the marl, and positively, because it retains moisture with great avidity. It is almost impossible to dry a marl containing much organic matter, and in any semi-dry or dry process this would be a very serious disadvantage. Organic matter in its coarser forms—i.e., roots, branches, twigs, etc., interferes greatly with the grinding of the marl, though the larger fragments are usually taken out by a separator early in the reducing process.

In the following table (155) are given the analyses of marls used at different American cement-plants, some quoted from published sources and others supplied by the chemists of the plants. A few of the quoted analyses are taken from prospectuses, but in general the analyses are of more satisfactory character. In all cases they are calculated dry, all water below 212° being neglected.

The analyses given in this table are mostly not picked analyses, such as are usually quoted in prospectuses, in which the marl rarely

TABLE 155.

ANALYSES OF MARLS USED IN AMERICAN CEMENT-PLANTS.

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Alkalies (K_2O, Na_2O).	Sulphur Trioxide (SO_3).	Carbon Dioxide (CO_2).	Organic Matter.
1	1.74	0.90	0.28	49.84	1.75	....	1.12	46.01	
2	1.78	1.21		49.55	1.30	....	1.58	40.35	4.23
3	0.85	0.86		51.04	1.31				
4	0.66	0.62		53.17	0.47	....	....	42.35	2.53
5	3.80	n. d.		51.10	1.54	....	0.24	41.82	1.50
6	0.19	0.05	0.07	51.31	1.93	....	0.14	42.40	2.25
7	0.22	0.76		51.56	1.26	....	....	46.20	
8	0.77	0.11		53.58	0.91	....	....	43.14	
9	1.24	0.80		50.90	1.43	....	....	41.54	4.09
10	0.72	0.24	0.12	55.12	0.44	....	tr.	43.77	
11	0.06	0.80		55.00	....	....	0.05	43.22	
12	1.19	0.55	0.25	52.50	1.16	1.84	tr.	42.51	n. d.
13	1.20	0.55	0.40	51.15	0.37	5.79	0.26	40.59	n. d.
14	n. d.	n. d.	n. d.	51.90	0.83	n. d.	0.20	41.67	n. d.
15	1.65	0.81		50.77	tr.	n. d.	0.66	39.89	n. d.
16	0.4	0.2	0.2	53.50	0.3	....	1.7		
17	0.42	1.08		52.36	1.01	....	2.01	42.26	0.86
18	0.26	0.10		52.86	0.18	....	....	41.73	1.54
19	0.26	0.21	0.01	50.98	0.19	....	....	40.26	1.68
20	6.22	1.70	0.86	47.86	0.04	2.20	....	42.11	
21	0.14	0.36		53.16	1.50				
22	0.54	0.56		54.40	2.34	....	....	42.20	
23	1.98	0.97		50.95	0.55	0.12	0.10	40.03	0.25
24	0.26	0.20		52.86	n. d.				
25	1.43	0.20	0.18	50.62	2.09	....	....	45.58	
26	0.46	0.44		54.44	0.30	....	....	43.10	1.12

1–2. Sandusky P. C. Co., Syracuse, Ind. S. B. Newberry, analyst. 25th Ann. Rep. Indiana Dept. Geology, p. 29, 182.
3. Wabash P. C. Co., Stroh, Ind. W. R. Oglesby, analyst. 25th Ann. Rep. Indiana Dept. Geology, p. 112.
4. Wabash P. C. Co., Stroh, Ind.
5. Millens P. C. Works, South Bend, Ind. H. H. Hooper, analyst. 25th Ann. Rep. Indiana Dept. Geology, p. 25.
6. Millens P. C. Works, South Bend, Ind. W. A. Noyes, analyst. 25th Ann. Rep. Indiana Dept. Geology, p. 273.
7. Peninsular P. C. Co., Cement City, Mich. J. G. Dean, analyst. Vol. 8, Mich. Geol. Survey, p. 236.
8. Newaygo P. C. Co., Newaygo, Mich. Lathbury and Spackman, analysts. Manufacturer's prospectus.
9. Newaygo P. C. Co., Newaygo, Mich. Vol. 8, Mich. Geol. Survey, p. 240.
10, 11. " " " Allerman, analyst. Manufacturer's prospectus.
12–13. Wolverine P. C. Co., Coldwater, Mich. H. E. Brown, analyst. Vol. 8, Mich. Geol. Survey, p. 247.
14 Wolverine P. C. Co., Coldwater, Mich. "Cement Industry," p. 78.
15. Bronson P. C. Co., Bronson, Mich. Mineral Industry, vol. 6, p. 99.
16. Iroquois P. C. Co., Caledonia, N. Y. 22d Ann. Rep. N. Y. State Geologist.
17. Millens P. C. Works, Wayland, N. Y.
18–19. Empire P. C. Co., Warners, N. Y.
20. Montezuma, N. Y. First marl used for cement. Mineral Industry, vol. 1, p. 52.
21. American C. Co., Jordan, N. Y.
22. Genesee Wayland P. C. Co., Perkinsville, N. Y.
23. Buckeye P. C. Co., Harper, Ohio. Mineral Industry, vol. 1, p. 52.
24. Castalia P. C. Co., Castalia, Ohio.
25. Imperial P. C. Co., Owen Sound, Ontario.
26. Canadian P. C. Co., Marlbank, Ontario. Rep. Ontario Bureau Mines, 1901, p. 16.

carries less than 98 per cent of lime carbonate. On the other hand some of them are still considerably better than can be expected in steady practice. The following data may throw some light on what sort of results are really obtained when a marl deposit is worked continuously.

First, as to water percentages: At a Michigan plant which takes its marl from under about 10 feet of water, an average of ten consecutive analyses gave the following results:

Silica (SiO_2)	0.07	
Alumina (Al_2O_3), Iron oxide (Fe_2O_3)	0.18	
Lime carbonate ($CaCO_3$)	39.80	(=CaO 22.29%)
Organic matter	0.59	
Water	59.36	

The marl in question is, it will be noted, very pure, being low in both clay and organic matter. The point to be noted is the high percentage of water each 100 lbs. of material dredged containing approximately only 40 lbs. of lime carbonate, with 60 lbs. of water. It must be borne in mind that this marl was not pumped to the plant, so that this large percentage of water represents only what was unavoidably taken up with the marl during dredging.

Second, as to purity: A long series of analyses of marl at another prominent Michigan plant gave the following limits of results. These are calculated on a *dry* basis, the 55 per cent or so of water which the marl carried when reaching the plant being neglected.

Silica (SiO_2)	1.40 to 8.60
Alumina (Al_2O_3)	0.55 " 1.30
Iron oxide (Fe_2O_3)	0.25 " 1.54
Lime (CaO)	54.60 " 46.20
Magnesia (MgO)	1.25 " 2.78
Carbon dioxide (CO_2)	42.90 " 36.30
Organic matter	0.05 " 10.50

It will be seen from these results that the manager should expect to receive material carrying often very high percentages of water and frequently containing a large amount of organic matter and other impurities.

Examining marl deposits.—Owing to the nature of the material and the physical conditions under which it occurs, the work of examining and valuing a marl deposit presents certain features of difficulty peculiar to itself. As in any other prospecting work, the two factors

which require determination are respectively the extent of the deposit and the composition of the material.

When the marl occurs in an old lake-bed overlain by soil or peat, the area can be roughly laid out into blocks or squares of convenient size, borings being made and samples taken at the corners of these squares. A pocket compass, or, better yet, the cheap "drainage level" made by Gurley and other instrument-makers, will suffice for laying out the work.

A marl deposit covered by water must be handled like any sounding proposition. The shore line should first be roughly surveyed, after which soundings and borings must be made from a raft or boat, the position of each boring being located by bearings taken to fixed points in the shore. A broad steady platform is necessary for the borings. This is afforded either by using a raft with a square opening in its center or by laying planks across the ends of two boats.

As the methods employed in determining the thickness and character of marl-beds are of a somewhat special character and are not fully described in current engineering text-books, the writer feels justified in introducing here a very detailed account of these methods by Mr. David J. Hale, of the Michigan Geological Survey. This account is taken almost verbatim from the paper cited below.*

In dealing with fairly solid marls not deeply covered with peat or soil, the simple outfit described below has proven very successful when manipulated with care. It is prepared as follows:

Weld an ordinary 2-inch auger on a $\frac{3}{8}$-inch gas-pipe 2 feet long. Thread the unwelded end of the pipe for coupling. Cut three lengths of pipe each in half or in four pieces if it is desired to carry the outfit long distances. Thread the ends of these sections for coupling. Get couplings enough to couple all together, so as to make a continuous hollow rod with attached auger. Insert a "T" coupling on the handle end, or end farthest from the auger, and pass a rod or stick through this so as to turn the outfit. A better way is to screw into each free end of the "T" a rod or piece of gas-pipe 18 inches long. Usually a pair of Stillson wrenches are needed to untwist the pipe, which becomes jammed during the boring.

Three-eighths-inch pipe, as above recommended, will be found to lift out much easier than half-inch, but will not do for deep boring; $\frac{3}{16}$-inch pipe is entirely too light and 1-inch pipe is too difficult to handle. A light, easily handled outfit is a great aid in boring, because the quicker the rod can be driven the less friction there will be to contend with, for

* Hale, D. J. The use of marl for cement manufacture. Vol. 8, pt. 3, Reports Mich. Geol. Survey, especially pp. 9–13, 108–110.

the marl particles will not have time to settle after each movement of the rod.

In boring, the handle should be twisted around as the rod is shoved down, even though the surface material may be soft enough to permit it to be driven down wi' out twisting, because if the latter method is adopted the surface ma.erial first taken up by the auger will cling to it during its descent, and will prevent securing a sample of the marl at lower depth. As each new length of pipe is added, the couplings should be firmly tightened, as neglect of this precaution may mean the loss of most of the outfit through uncoupling while it is being drawn up.

This device gives good results when employed on a fairly dense marl not deeply covered by peat or grass, because the auger will clear itself of the surface material on the way down and will retain fairly well the clean sample taken at the bottom.

In heavily covered marl-beds, or in dealing with very fluid marls, other boring devices must be tried. A clumsy but efficient type of sampler for this purpose is made as follows: Take a 2-foot length of 1-inch gas-pipe and thread one end for coupling. Screw reducers on the coupled end until the last reducer can take a $\frac{3}{8}$-inch or $\frac{1}{2}$-inch pipe, any necessary number of lengths of which pipe will form the rod proper. Sharpen the open edge of the 1-inch pipe and fit into it a plug with a shoulder that fits against the rim, allowing the plug to penetrate $\frac{1}{2}$ inch into the open end of the pipe. Sharpen the end of the plug opposite the shoulder and bore a hole lengthwise through the plug. Pass a $\frac{3}{16}$-inch iron rod through the plug from the shoulder end and bolt it by screwing a nut upon the end opposite the shoulder, which end should be sharpened so as to penetrate the marl more easily. The end of the rod may be threaded for several inches and a nut screwed on, then pass the end of the rod through the plug and screw the nut tight against the plug. This will hold the plug in place during boring and withdrawing. The rod is inserted in the 1-inch pipe and passed up through that and the $\frac{3}{8}$-inch pipe, from the upper end of which the free end of the rod may project. The rod gives a means of either closing firmly or opening the bottom end of the 1-inch pipe. When boring the plug is held firmly against the mouth of the pipe by means of the rod, and the whole apparatus is shoved down into the marl to the desired depth. The pipe is then raised, while the rod is held stationary; the apparatus is held in this position a moment to allow the marl to close in about the rod and then the pipe is lowered until the plug closes it. With the plug held firmly the entire apparatus is raised to the surface, the plug loosened, and

the sample of marl taken out of the section of 1-inch pipe. This device can be driven through and withdrawn from a marl-bed covered by peat, grass, etc., and still the marl sample can be preserved from intermixture with these materials.

A borer invented and manufactured by Robert G. Hunt & Co. is also noted by Mr. Hale. This consists of a piece of steel about 18 feet long, much the shape of the half of a long gun-barrel split longitudinally. The end which first enters the marl is capped and pointed with steel so that it will penetrate more easily, while the other end is provided with a handle for raising the apparatus. The two vertical edges of the barrel are sharpened so as to cut the marl. When the instrument has been driven down to the desired depth it is turned half around, filling the half cylinder with marl for its entire length, and then withdrawn. This gives a perfect sample of the bed from top to bottom.

The various devices above described will generally give satisfactory results when operating in moderate depths of water and on any but the most fluid marls. For these latter, as well as for sampling in deep water, special devices are required, which are described by Mr. Hale in the paper cited. But in examining deposits of marl to be used as Portland-cement material the very deep and very fluid marls may be dismissed without sampling. For under present economic conditions such materials could not be profitably used in cement-manufacture.

After the results of the borings have been plotted in such a way as to give both depth of water and thickness of marl, the amount of marl available can be calculated quite closely. In making these estimates it will be safest to assume that each cubic yard of marl in the lake will yield 900 lbs. of *dry* marl, or sufficient to make two barrels of cement. A 1000 bbl. plant should therefore own about 3,000,000 cubic yards of marl, which would insure a twenty-year supply of raw material.

List of references on marls.—Of the following papers on marls, those dealing chiefly with the origin of marl deposits are marked *A*; those describing the deposits of certain States or areas are marked *B*; and those discussing the technology of marls as cement materials are marked *C*:

A, B. Blatchley, W. S., and Ashley, G. H. The lakes of northern Indiana and their associated marl deposits. 25th Ann. Rep. Indiana Dept. Geology and Natural Resources, pp. 31–321. 1901.

A. Davis, C. A. A contribution to the natural history of marl. Journal of Geology, vol. 8, pp. 485–497. 1900.

A. Davis, C. A. A remarkable marl lake. Journal of Geology, vol. 8, pp. 498–500. 1900.

A. Davis, C. A. Second contribution to the natural history of marl. Journal of Geology, vol. 9, pp. 491–506. 1901.

A. Davis, C. A. A contribution to the natural history of marl. Vol. 8, pt. 3, Reports, Michigan Geological Survey, pp. 65–103. 1903.

B, C. Eckel, E. C. Cement materials and cement industries of the United States. Bulletin 243, U. S. Geological Survey. 1905.

B. Ells, R. W. Marl deposits of eastern Canada. Ottawa Naturalist, vol. 16, pp. 59-69. 1902.

B. Fall, D. Marls and clays in Michigan. Vol. 8, pt. 3, Reports Michigan Geological Survey, pp. 343–348. 1903.

A, B, C. Hale, D. J. Marl and its application to the manufacture of Portland cement. Vol. 8, pt. 3, Reports Michigan Geological Survey, pp. 1–64, 103–190. 1903.

A. Lane, A. C. Notes on the origin of Michigan bog-limes. Vol. 8, pt. 3, Reports Michigan Geological Survey, pp. 199–223. 1903.

B, C. Lane, A. C. List of marl localities and Portland-cement mills in Michigan. Vol. 8, pt. 3, Reports Michigan Geological Survey, pp. 224–342. 1903.

C. Lathbury, B. B. The development of marl and clay properties for the manufacture of Portland cement. Vol. 8, pt. 3, Reports Michigan Geological Survey, pp. 191–198. 1903.

B. Ries, H. Lime and cement industries of New York. Bulletin 44, New York State Museum, pp. 326. 1901.

A, B. Russell, I. C. The Portland-cement industry in Michigan. 22d Ann. Rep. U. S. Geol. Survey, pt. 3, pp. 629–685. 1902.

C. Spackman, H. S. The manufacture of cement from marl and clay. Proc. Engineers' Club of Phila., April, 1903. Engineering News, vol. 49, pp. 492–494. June 4, 1903.

CHAPTER XXIV.

ALKALI WASTE: BLAST-FURNACE SLAG.

THE two raw materials to be discussed in the present chapter agree in being waste products or by-products of other industries which, because of their chemical composition, can be used in Portland-cement manufacture. In almost every other respect they differ. Alkali waste is a fine-grained, soft and pure form of lime carbonate. Slag is very hard, coarse-grained, and is composed of lime (CaO), silica, and alumina.

Waste products or by-products can, of course, be usually obtained at a low or nominal cost, and on this account both slag and alkali waste assume an importance entirely out of proportion to their other properties. But it must be recollected that as by-products their production and quality depend entirely upon the condition of the industries of which they are wastes, and that no furnace manager or alkali-works superintendent will run his plant solely in order to turn out a by-product regular in amount and composition. For this reason it is essential that a cement-plant using a waste product must be closely identified in ownership with the furnace or works which furnishes this waste product. Common ownership is practically the only way of insuring a sufficient and regular supply of satisfactory composition.

Alkali Waste.

A large amount of waste material results from the processes used at alkali works in the manufacture of caustic soda. This waste material is largely a precipitated form of calcium carbonate, and if sufficiently free from injurious impurities, furnishes a cheap source of lime for use in Portland-cement manufacture. The value of the waste for this purpose depends largely on the process from which it resulted.

Leblanc-process waste.—The waste resulting from the Leblanc process carries a very large percentage of sulphur, mostly in the form of lime sulphides, carried over from the pyrites used in the process. A fairly typical analysis * of Leblanc-process waste is given below and will serve to show the composition of this material:

* Kingzett, C. T. The Alkali Trade, p. 134.

Lime carbonate ($CaCO_3$)	41.20
Lime sulphate ($CaSO_4$)	2.53
Lime hydrate (CaH_2O_2)	8.72
Lime disulphide (CaS_2)	5.97
Lime sulphide (CaS)	25.79
Sodium sulphide (Na_2S)	1.44
Magnesium silicate ($MgSiO_3$)	3.63
Phosphates of iron and alumina	8.91

This material is obviously unfit for use in the manufacture of Portland cement. Attempts have been made to recover the sulphur contained in the waste, but the removal of this constituent is never sufficiently perfect to permit the resulting waste to be of use to the cement manufacturer.

Ammonia-process waste.—The waste from ammonia-process works is, on the contrary, a very pure mass of precipitated lime, mostly in the carbonate form, though some lime hydrate is always present. As pyrite is not used in this process, the sulphur in the waste is commonly well within Portland-cement limits. The magnesia content of the waste may or may not be high, according to the character of the limestone that has been used in the process of soda-manufacture. When a pure limestone low in magnesium carbonate has been used, the waste will be low in magnesia and is then a very satisfactory Portland-cement material. The following analyses are representative of the waste obtained at alkali-plants using the ammonia process.

TABLE 156.

ANALYSES OF ALKALI WASTE, AMMONIA PROCESS.

	1.	2.	3.	4.	5.
Silica (SiO_2)	0.60	1.98	1.75	n. d.	0.98
Alumina (Al_2O_3)	3.04	1.41	0.61	2.20	1.62
Iron oxide (Fe_2O_3)		1.38			
Lime (CaO)	53.33	48.29	50.60	52.40	50.40
Magnesia (MgO)	0.48	1.51	5.35	3.75	4.97
Alkalies (K_2O,Na_2O)	0.20	0.64	0.64	0.20	0.50
Sulphur trioxide (SO_3)	n. d.	1.26	n. d.	n. d.	n. d.
Sulphur (S)	n. d.	n. d.	0.10	n. d.	0.06
Carbon dioxide (CO_2)	42.43	39.60	41.70	41.17	n. d.
Water	n. d.	3.80		n. d.	n. d.

The analyses given in the above table are of alkali wastes which have at one time or another been used in the manufacture of Portland cement either in the United States or in England. The effect on the waste when a magnesian limestone is used in the alkali-plant is well

shown by analyses 3, 4 and 5, in all of which the magnesia is high for a Portland-cement material.

At the only American cement-plant which uses alkali waste the materials (clay and waste) are mixed wet. The waste carries 90 to 95 per cent of lime carbonate, while the clay used gives the following analysis:

Silica (SiO_2)	63.54
Alumina (Al_2O_3) and Iron oxide (Fe_2O_3)	24.00
Lime (CaO)	1.66
Magnesia (MgO)	1.05
Alkalies (K_2O,Na_2O)	0.78
Carbon dioxide (CO_2)	2.47
Water	7.05

The clay is put through a rotary drier and ground in a dry-pan, after which the waste and clay are mixed in a wet pug-mill and ground in wet tube mills. The mix is made drier than at most of the plants using marl and contains usually about 40 per cent of water.

It is not, of course, necessary that wet mixing should be practiced when alkali waste is employed as one raw material. The waste could be dried, though it is possible that its physical properties might render this more difficult than drying limestones or clays.

List of references on alkali waste as a cement material.—The following brief list covers the few available references on this subject:

Butler, D. B. [Alkali waste used in England.] Portland Cement: its Manufacture, Testing, and Use, pp. 25–27. 1899.

Lathbury, B. B. The Michigan Alkali Company's plant for manufacturing Portland cement from caustic-soda waste. Engineering News, June 7, 1900.

Lathbury, B. B., and Spackman, H. S. The Michigan Alkali Company's plant, Wyandotte, Michigan. The Rotary Kiln, pp. 110–119. 1902.

Redgrave, G. R. [Use of alkali waste in England.] Calcareous Cements: their Nature and Uses, pp. 182–184. 1805.

Blast-furnace Slag.

True Portland cements, which must be sharply distinguished from the slag (or puzzolan) cements described in Part VII of this volume, can be made from mixtures which contain blast-furnace slag as one ingredient. In this case the slag is intimately mixed with limestone and the mixture is finely powdered. It is then burned in kilns and the resulting clinker pulverized.

The slags from iron furnaces consist essentially of lime (CaO), silica (SiO_2), and alumina (Al_2O_3), though small percentages of iron oxide (FeO), magnesia (MgO), and sulphur (S) are commonly present. Slag may therefore be regarded as a very impure limestone or a very calcareous clay from which the carbon dioxide has been driven off.

Two plants are at present engaged in the United States in the manufacture of true Portland cement from slag, and there seems to be no reason why this cheap and satisfactory raw material should not become an important factor in the cement industry of the country.

Slags in general.—Slags are the fusible silicates formed, during the smelting or refining of metals, by the combination of the fluxing materials with the gangue of the ore. The composition of the slag, therefore, will be determined by the composition and relative proportions of the fluxes and the gangue. In general, the slag will contain only those elements which are present in either the gangue or the flux, though it may carry also a percentage, usually small, of the metal which is being smelted or treated. In some processes also the composition of the slag may be slightly modified through the action of the fuel, from which certain impurities may be taken up.

While many elements may occur in slags, those which are of universal or even common occurrence are comparatively few. The slags commonly found in iron metallurgy consist essentially of silica, alumina, iron oxide, and lime, with or without magnesia. Alkalies, sulphur, and phosphorus are also almost invariably present, but in small percentages.

The following analyses of slags from various furnaces will serve to give some idea of the range in composition of these products.

TABLE 157.

ANALYSES OF IRON-FURNACE SLAGS.

Silica (SiO_2)	30.00	30.72	32.51	32.90	26.88	31.65
Alumina (Al_2O_3)	28.00	16.40	13.91	13.25	24.12	17.00
Iron oxides (FeO,Fe_2O_3)	0.75	0.43	0.48	0.46	0.44	0.65
Lime (CaO)	32.75	48.59	44.75	47.30	45.11	47.20
Magnesia (MgO)	5.25	1.28	2.20	1.37	1.09	1.36
Lime sulphide (CaS)	1.90	2.16	4.90	3.42	1.86	n. d.
Silica (SiO_2)		28.35	38.00	31.50	32.20	33.10
Alumina (Al_2O_3)		18.15	10.00	18.56	15.50	12.60
Iron oxides (FeO,Fe_2O_3)		1.50	n. d.	n. d.	n. d.	n. d.
Lime (CaO)		47.40	46.0	42.22	48.14	49.98
Magnesia (MgO)		2.45	n. d.	3.18	2.27	2.45
Lime sulphide (CaS)		n. d.	n. d.	n. d.	n. d.	n. d.

Slags used as Portland-cement materials.—The slags used in Portland-cement manufacture are iron blast-furnace slags of the more basic types—i.e., those in which the lime (CaO) reaches 30 per cent or over. The higher the lime, up to say 50 per cent, the more valuable the slag for this use. The composition of the slags will usually be controlled, however, by the requirements of the furnaces, not by the needs of the cement-plant.

The following shows the range in composition of the slags used at a German Portland-cement plant:

ANALYSES OF SLAG USED IN PORTLAND-CEMENT MANUFACTURE

	Per Cent.
Silica (SiO_2)	30 to 35
Alumina (Al_2O_3)	10 " 14
Iron oxide (FeO)	0.2 " 1.2
Lime (CaO)	46 " 49
Magnesia (MgO)	0.5 " 3.5
Sulphur trioxide (SO_3)	0.2 " 0.6

As a Portland-cement material slag possesses one great advantage in addition to its cheapness. This advantage is chemical, and is due to the fact that the lime contained in the slag is present in the form of oxide (CaO), instead of carbonate ($CaCO_3$), as in limestones. It does not require to be decarbonated, and therefore a mixture made up of slag and clay will clinker with less fuel than one consisting of limestone and clay.

Opposed to this chemical advantage is a physical disadvantage. If the slag is allowed to cool as it issues from the furnaces, it solidifies into very hard and tough masses much more resistant than the hardest of limestones. In order to avoid this difficulty, it is the common practice to " granulate " the slag, i.e., to run it direct from the furnace into cold water. This proceeding breaks up the slag into little porous granules $\frac{1}{10}$ to $\frac{1}{2}$ inch in diameter, and incidentally removes part of the sulphur contained in the slag. But to offset these gains, it introduces a large amount of water into the product, so that a granulated slag may carry from 20 to 40 per cent of water, and this greatly increases the cost of drying.

As the chemical and physical properties of slag introduce certain interesting features into the manufacture of Portland cement from a limestone-slag mixture, this mixture will be discussed separately on later pages.

CHAPTER XXV.

CLAYS, SHALES, AND SLATES.

EXCEPT when a very clayey limestone or a slag is one component of a Portland-cement mixture, the silica, alumina and iron oxide necessary for the mix are always supplied in the form of clay, shale, or slate.

The materials known respectively as clays, shales, and slates are of practically the same composition and ultimate origin, but differ in their degree of consolidation.

Clays are ultimately derived from the decay of older rocks, the finer particles resulting from this decay being carried off and deposited by streams along their channels, in lakes, or along parts of the seacoast or sea-bottom as beds of clay. In chemical composition the clays are composed essentially of silica and alumina, though iron oxide is almost invariably present in more or less amount, while lime, magnesia, alkalies, and sulphur are of frequent occurrence, though usually only in small percentages.

Shales are clays which have become hardened by pressure. The so-called "fire-clays" of the Coal Measures are shales, as are many of the other "clays" of commerce. The slates include those clayey rocks which through pressure have gained the property of splitting readily into thin parallel leaves.

Clays.

The term clay is applied to fine-grained unconsolidated materials which possess the property of plasticity when wet, while they lose this property and harden on being strongly heated. Being, as explained below, the finer débris resulting from the decay of many different kinds of rocks, the clays will naturally differ greatly among themselves in composition, etc.

Origin of clays.—When rocks of any kind are exposed to atmospheric action, more or less rapid disintegration sets in. This is due partly to chemical and partly to physical causes. It is hastened, for example, by the dissolving out of any soluble minerals that may occur in the rock, by the expansion and contraction due to freezing, and by the

action of the organic acids set free by decaying vegetable matter. The more soluble ingredients of the rock are usually removed in solution by surface or percolating waters, while the more insoluble portions are either left behind or are carried off mechanically by streams. These relatively insoluble materials when sufficiently fine grained constitute the clays. When they are left as a deposit in the spot where the original rock disintegrated, they are called *residual* clays; when they are carried off by surface-waters and finally deposited in the sea or along river-beds they are *transported* or *sedimentary* clays. A third class of particular interest to the cement manufacturer are the *glacial* clays, deposited under or in front of the glaciers which formerly covered most of the Northern States.

Based on the facts above stated as to origin and deposition, clayey materials may be classified as follows:

A. *Residual clays*, resulting from the decay in place of pre-existing rocks. According to the parent rock the clays may be derived,
  A 1. From decay of more or less clayey limestones.
  A 2. From decay of shales or slates.
  A 3. From decay of igneous rocks.

B. *Transported clays*, resulting from the transportation by water (or more rarely by ice or wind) of either the residual clays of Class A or of other finely ground rock; and the deposition of such material at more or less distance from its point of origin: The sub-classes are:
  B 1. Water-borne clays; carried by water and deposited
    (*a*) In sea basins.
    (*b*) Along stream valleys.
    (*c*) In lakes.
  B 2. Ice-borne or glacial clays.
  B 3. Wind-borne clays.

Composition of clays.—The residual, sedimentary and glacial clays usually differ markedly in composition, owing to the different manner in which they have been deposited. The residual clays, for example, are apt to contain coarse fragments of any very insoluble and hard material which the original rock may have contained. A residual clay arising from the decay of a granite will probably contain fragments of quartz; one derived from a limestone may contain chert or flint, as well as masses of undissolved lime carbonate. A sedimentary

clay, on the other hand, having been transported by water for great distances, has usually lost all its coarser material and is a fine-grained and homogeneous product. The glacial clays, being formed mechanically by the abrading power of the ice, show even less homogeneity than the residual clays, and are apt to contain much sand, gravel, and pebbles.

Clays used in Portland-cement manufacture.—For use as Portland-cement materials clays should be as free as possible from gravel and sand, as the silica present as pebbles or grit is practically inert in the kiln unless ground more finely than is economically practicable. In composition they should not carry less than 55 per cent of silica, and preferably from 60 to 70 per cent. The alumina and iron oxide together should not amount to more than one-half the percentage of silica, and the composition will usually be better the nearer the ratio $Al_2O_3+Fe_2O_3=\frac{SiO_2}{3}$ is approached.

Nodules of lime carbonate, gypsum, or pyrite, if present in any quantity, are undesirable; though the lime carbonate is not absolutely injurious. Magnesia and alkalies should be low, preferably not above 3 per cent.

The clays actually used in cement plants may be separated, for convenience, into the *normal* clays and the *limey* clays. In this section the dividing line between these classes will be fixed arbitrarily at 5 per cent of lime (CaO) and magnesia (MgO) together, all clays containing over 5 per cent of both oxides being called limey clays, while those carrying less than 5 per cent are termed normal clays.

Shales.

It has been noted above that shales are simply clays which have been hardened by pressure. This statement, while approximately correct, requires some restriction. For the shales were formed almost entirely from extensive deposits of clays of marine origin, and therefore do not show the same irregularities of composition, etc., that modern clays exhibit. Shales, for example, rarely are so full of coarse sand and gravel as the glacial clays of Michigan and other Northern States.

TABLE 158.

ANALYSES OF NORMAL CLAYS USED IN AMERICAN CEMENT-PLANTS.

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Alkalies (K_2O,Na_2O).	Sulphur Trioxide (SO_3).	Carbon Dioxide (CO_2).	Water.	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$.
1	53.30	23.29	9.52	0.36	1.49	n. d.	n. d.	n. d.	n. d.	1.62
2	65.12	19.05	7.66	0.34	0.31	n. d.	n. d.	n. d.	n. d.	2.44
3	63.73	22.12	9.01	2.83	....	0.21	n. d.	n. d.	n. d.	2.04
4	53.21	15.91	7.25	1.89	0.99	2.21	0.97	17.21		2.29
5	59.10	25.41		3.61	0.87	1.10	0.31	9.81		2.32
6	58.02	26.12		3.70	1.00	1.55	0.33	9.27		2.22
7	57.25	26.15		3.09	1.10	1.88	0.39	9.30		2.19
8	58.25	18.56	7.35	3.10	1.28	2.35	0.45	8.55		2.25
9	74.29	12.06	4.92	0.41	0.68	2.56	n. d.	n. d.	n. d.	4.39
10	63.54	24.00		1.66	1.05	0.78	....	2.47	7.05	2.65
11	64.65	24.31		1.16	1.92	n. d.	n. d.	n. d.	n. d.	2.66
12	60.28	27.10		1.26	n. d.	n. d.	n. d.	8.38		2.22
13	60.30	29.78		1.98	n. d.	n. d.	n. d.	8.30		2.03
14	61.40	25.08		1.40	n. d.	n. d.	n. d.	6.60		2.45
15	63.82	25.36		3.42	n. d.	n. d.	n. d.	6.96		2.52
16	63.07	24.00		3.00	1.20	n. d.	n. d.	8.80		2.63
17	61.92	16.58	7.84	2.01	1.58	3.64	tr.	n. d.	n. d.	2.53
18	65.68	24.08		2.01	1.75	n. d.	n. d.	n. d.	n. d.	2.73
19	62.5	20.2	7.5	0.8	1.8	n. d.	0.4	n. d.	n. d.	2.26
20	58.90	27.50		4.08	0.79	n. d.	n. d.	n. d.	n. d.	2.14
21	59.10	24.01		2.20	2.00	n. d.	n. d.	n. d.	n. d.	2.46
22	64.85	17.98	5.92	2.24	1.40	n. d.	n. d.	4.98		2.82
23	58.04	14.63	9.27	1.53	2.02	n. d.	0.37	12.67		2.33

1, 2. Whitecliffs P. C. Co., Whitecliffs, Ark. Trans Amer. Inst. Mining Engrs., vol. 21.
3. Santa Cruz, Calif. Mineral Industry, vol. 1, p. 52.
4.–8. Pacific P. C. Co., Suisun, Calif. J. C. Wheeler, analyst.
9. Bedford P. C. Co., Bedford, Ind. A. W. Smith, analyst. 25th Ann. Rep. Indiana Dept. Geology, p. 328.
10. Wyandotte P. C. Co., Wyandotte, Mich.
11. Peerless P. C. Co., Union City, Mich. Lundteigen, analyst.
12.–16. Peninsular P. C. Co., Cement City, Mich.
17. Catskill P. C. Co., Smiths Landing, N. Y.
18. American Cement Co., Jordan, N. Y.
19. Iroquois P. C. Co., Caledonia, N. Y.
20. Hudson P. C. Co., Hudson, N. Y. Heiberg and Roney, analysts.
21. Castalia P. C. Co., Castalia, Ohio.
22. Omega P. C. Co., Jonesville, Mich. Vol. 8, Mich. Geol. Survey, p. 229.
23. Almendares P. C. Co., Marinao, Cuba. Engineering Record, vol. 49, p. 37.

TABLE 159.

ANALYSES OF LIMEY CLAYS USED IN AMERICAN CEMENT-PLANTS.

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Alkalies (K_2O, Na_2O).	Sulphur Trioxide (SO_3).	Carbon Dioxide (CO_2).	Water.	$\frac{Silica}{Al_2O_3+Fe_2O_3}$.
1	47.5	33.0		4.0	2.0	1.5	n. d.	13.5		1.44
2	61.70	18.00		8.40	2.91	n. d.	n. d.	13.30		3.43
3	57.74	17.76		7.80	3.52	n. d.	n. d.	12.30		3.25
4	56.74	19.43	4.83	7.27	3.05	n. d.	n. d.	10.39		2.34
5	55.27	10.20	3.40	9.12	5.73	n. d.	n. d.	n. d.	n. d.	4.06
6	40.56	8.52	2.84	20.94	1.32	1.97	n. d.	17.90	5.95	3.57
7	59.36	10.01		23.80	2.40	0.58	1.71	....	2.05	5.93
8	58.05	25.50		2.50	3.24	n. d.	n. d.	8.80		2.27
9	46.40	16.30		14.20	2.06	0.75	n. d.	23.40	7.00	2.85
10	46.81	14.21		14.04	3.61	3.04	1.18	15.75	n. d.	3.29
11	55.84	8.90	3.02	9.98	5.16	n. d.	n. d.	13.68		4.69
12	55.27	28.15		5.84	2.25	n. d.	0.12	n. d.	n. d.	1.96
13	45.21	19.08	6.74	11.17	1.57	n. d.	1.55*	10.47	4.17	1.75
14	50.08	14.50	4.61	6.62	4.40	5.10	n. d.	n. d.	n. d.	2.62
15	40.48	20.95		14.45	0.47	3.14	n. d.	11.87	8.50	1.93
16	42.85	13.51	4.49	12.69	3.32	3.08	2.85	13.57	n. d.	2.38
17	53.50	24.20		5.15	2.15	n. d.	n. d.	14.10		2.21
18	52.00	31.00		7.10	3.33	n. d.	n. d.	n. d.	n. d.	1.68
19	52.10	35.56		5.90	3.33	n. d.	n. d.	n. d.	n. d.	1.46
20	51.56	14.50	3.84	9.80	n. d.	n. d.	tr.	7.70	n. d.	2.81
21	47.45	19.85		17.80	0.09	4.34	1.03	n. d.	n. d.	2.39
22	60.16	28.58		1.97	6.56	n. d.	n. d.	n. d.	n. d.	2.10
23	59.18	27.74		1.89	8.65	n. d.	n. d.	n. d.	n. d.	2.13
24	54.96	23.09	5.03	14.57	1.37	0.48	0.57	n. d.	n. d.	1.95
25	41.69	14.86	6.71	12.80	4.96	2.24	n. d.	16.74		1.93
26	39.23	12.13	2.79	21.61	2.69	1.69	n. d.	19.84		2.63
27	53.32	24.22		7.17	2.05	n. d.	n. d.	7.85	n. d.	2.20

* $CaSO_4$.

1. California P. C. Co., Colton, Cal.
2.–4. Wabash P. C. Co., Stroh, Ind.
5. Sandusky P. C. Co., Syracuse, Ind. 25th Ann. Rep. Indiana Dept. Geology, p. 28.
6. Monolith P. C. Co., Bristol, Ind. 21st Ann. Rep. U. S. Geol. Survey, pt. 6, p. 400.
7. Millens P. C. Works, South Bend, Ind. 25th Ann. Rep. Indiana Dept. Geology, p. 25.
8. Peninsular P. C. Co., Cement City, Mich.
9. Wyandotte P. C. Co., Wyandotte, Mich. 22d Ann. Rep. U. S. Geol. Survey.
10. " " " " Lathbury and Spackman, analysts. Engineering News, vol. 43, p. 373.
11. Newaygo P. C. Co., Newaygo, Mich. Prospectus.
12. Glens Falls P. C. Co., Glens Falls, N. Y. Mineral Industry, vol. 6, p. 97.
13. Millen P. C. Co., Wayland, N. Y.
14. Montezuma P. C. Co., Montezuma, N. Y. Mineral Industry, vol. 1, p. 52.
15.–16. Empire P. C. Co., Warners, N. Y. Cummings, "American Cements," p. 253.
17. Genesee P. C. Co., Wayland, N. Y.
18, 19. Hudson P. C. Co., Hudson, N. Y. Heiberg and Roney, analysts.
20. Castalia P. C. Co., Castalia, Ohio.
21. Buckeye, P. C. Co., Harper, Ohio. Mineral Industry, vol. 1, p. 52.
22, 23. Clay used for reducer at a plant in the Lehigh district, Pa.
24. Orangeville, Ontario, Canada. Report Ontario Bureau of Mines, 1901.
25, 26. Imperial P. C. Co., Owen Sound, Ontario, Canada.
27. Canadian P. C. Co., Marlbrook, Ontario, Canada.

TABLE 160.

ANALYSES OF NORMAL SHALES USED IN AMERICAN CEMENT-PLANTS.

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Alkalies (K_2O,Na_2O).	Sulphur Trioxide (SO_3).	Carbon Dioxide (CO_2).	Water.	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$.
1	57.98	18.26	4.57	1.75	1.83	n. d.	1.28	12.08		
2	65.99	21.57	6.07	0.47	0.82	n. d.	n. d.	n. d.	n. d.	
3	63.30	26.00		1.25	1.25	n. d.	n. d.	n. d.	6.25	
4	63.56	27.32		1.20	1.20	n. d.	n. d.	n. d.	n. d.	
5	55.80	30.20		1.16	n. d.	n. d.	n. d.	n. d.	n. d.	
6	56.30	29.86		n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	
7	60.00	23.26	4.32	0.90	1.12	n. d.	n. d.	6.16		
8	62.67	19.99	5.46	1.25	0.72	n. d.	n. d.	n. d.	n. d.	
9	60.15	19.78	9.10	0.52	0.10	n. d.	tr.	n. d.	n. d.	
10	60.97	20.66	6.59	0.65	1.13	n. d.	tr.	n. d.	n. d.	
11	55.00	21.79	9.26	n. d.	n. d.	n. d.	n. d.	8.61		
12	54.70	31.68		1.15	n. d.	n. d.	n. d.	n. d.	n. d.	1.72
13	64.30	33.60		1.46	1.30	n. d.	n. d.	n. d.	n. d.	1.91
14	70.20	26.90		n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	2.61
15	61.09	19.19	6.78	2.51	0.65	3.16	1.42	5.13		
16	61.15	18.47	5.05	0.98	2.26	n. d.	0.91	7.02		
17	58.24	18.56	7.68	0.61	0.24	n. d.	n. d.	10.04		
18	59.64	19.14	7.59	0.26	2.31	4.33	n. d.	4.71		
19	62.10	20.09	7.81	0.65	0.96	n. d.	0.49			
20	59.02	29.84		0.68	2.16	n. d.	n. d.	n. d.	n. d.	
21	58.44	27.45		1.16	2.23	n. d.	n. d.	n. d.	n. d.	
22	58.90	27.25		1.23	2.18	n. d.	n. d.	n. d.	n. d.	
23	58.92	27.00		1.41	2.32	n. d.	n. d.	n. d.	n. d.	
24	60.24	30.04		2.21	1.55	n. d.	n. d.	n. d.	n. d.	2.01
25	60.02	26.60		2.31	1.62	n. d.	n. d.	n. d.	n. d.	

1. Western P. C. Co., Yankton, S. D. Mineral Industry, vol. 6, p. 97.
2. Crescent P. C. Co., Wampum, Pa.
3. Wellston P. C. Co., Wellston, Ohio. W. S. Trueblood, analyst.
4–7. Ironton P. C. Co., Ironton, Ohio. C. D. Quick, analyst.
8–11. Diamond P. C. Co., Middle Branch, Ohio. E. Davidson, analyst.
12–14. Hudson P. C. Co., Hudson, N. Y. Heiberg and Roney, analysts.
15. Alpena P. C. Co., Alpena, Mich. Vol. 8, pt 3, Reports Mich. Geol. Survey, p. 227.
16. Wolverine P. C. Co., Coldwater, Mich.
17. Michigan P. C. Co., Coldwater, Mich. Cement Industry, p. 78.
18. Lehigh P. C. Co., Mitchell, Ind. 26th Ann. Rep. Indiana Dept. Geology, p. 276.
19. Bronson P. C. Co., Bronson, Mich. Mineral Industry, vol. 6, p. 99.
20. Peerless P. C. Co., Union City, Mich. Lundteigen, analyst.
22–25. Cayuga P. C. Co., Portland Point, N. Y. J. H. McGuire, analyst.

The limey shales are almost exclusively shales which occur interbedded, in comparatively thin layers, with limestones. Occasionally a limey shale will owe its content of lime almost entirely to the fossil shells it contains, the remainder of the shale being practically free from carbonates. For both of the above reasons limey shales are apt to be a source of trouble in the practical working of a plant and require considerable care in quarry management to insure that the raw materials are anywhere near uniform in composition from day to day.

FIG. 69.—Pit in heavy shale-bed.

FIG. 70.—Shale-pit worked on two levels.

TABLE 161.

ANALYSES OF LIMEY SHALES USED IN AMERICAN CEMENT-PLANTS.

	Silica (SiO_2).	Alumina (Al_2O_3).	Iron Oxide (Fe_2O_3).	Lime (CaO).	Magnesia (MgO).	Sulphur Trioxide (SO_3).	Carbon Dioxide (CO_2).	Water.	$\frac{SiO_2}{Al_2O_3+Fe_2O_3}$.
1	53.12	20.60	4.09	4.02	2.24	n. d.	13.70		2.15
2	54.30	19.33	5.57	3.29	2.57	2.36	n. d.	n. d.	
3	52.74	21.73		12.37	2.01	n. d.	11.27	n. d.	
4	54.4	18.2	5.7	7.2	1.8	n. d.	12.3		
5	54.18	19.17	6.11	7.05	1.89	n. d.	11.95		
6	56.0	22.1		8.0	1.5	tr.	10.7		2.53
7	57.45	20.56	2.78	4.27	3.17	0.35	8.15		
8	55.96	22.44	2.80	3.78	3.22	0.74	8.03		
9	58.22	17.68	4.48	3.82	2.85	0.43	7.83		
10	57.50	21.70		12.19	1.93	n. d.	n. d.	n. d.	
11	57.82	21.76		8.32	1.81	n. d.	n. d.	n. d.	
12	38.84	17.76		21.58	1.78	n. d.	n. d.	n. d.	
13	50.48	8.89		23.74	2.21	n. d.	n. d.	n. d.	5.68
14	46.54	21.50		11.51	1.88	n. d.	n. d.	n. d.	
15	46.72	22.00		11.82	2.11	n. d.	n. d.	n. d.	
16	56.50	24.50		5.14	1.78	n. d.	n. d.	n. d.	2.31
17	58.10	26.14		3.34	2.01	n. d.	n. d.	n. d.	
18	58.25	24.18		3.46	2.10	n. d.	n. d.	n. d.	
19	61.94	11.58	3.49	5.92	4.85	.18	n. d.	n. d.	
20	56.64	12.18	3.59	8.17	4.29	.31	n. d.	n. d.	
21	61.10	13.91	3.62	6.32	3.91	.31	n. d.	n. d.	
22	59.36	12.38	3.62	5.63	4.62	.30	n. d.	n. d.	
23	53.63	24.47		5.94	1.79	n. d.	10.03		2.19

1. Chicago P. C. Co., Oglesby, Ill. Manufacturer's circular.
2. Marquette Cement Co., Oglesby, Ill. 25th Ann. Rep. U. S. Geol. Survey, pt. 6, p. 544.
3. German-American P. C. Works, La Salle, Ill. W. E. Prüssing, analyst.
4, 5. Iola P. C. Co., Iola, Kansas.
6. Kansas P. C. Co., Iola, Kansas.
7–9. Alpena P. C. Co., Alpena, Mich.
10–18. Cayuga P. C. Co., Portland Point, N. Y. J. H. McGuire, analyst.
19–22. Bronson P. C. Co., Bronson, Mich. W. H. Simmons, analyst. Vol. 8, Mich. Geol. Survey, p. 239.
23. Virginia P. C. Co., Craigsville, Va. "Cement Industry," p. 235.

Examination of clay deposits.—Most of the notes in relation to examining limestone deposits presented on an earlier page will apply to the report on a deposit of clay or shale. In sampling, however, the earth-auger can be used much more extensively, as the clayey materials are usually soft enough to be bored readily by such means. For valuable notes on the use of the auger, reference should be made to the papers cited below.*

* Bleininger, A. V. The manufacture of hydraulic cements. Bulletin 4, Ohio Geol. Survey, pp. 102–108. 1904. Catlett, C. The hand-auger and hand-drill in prospecting work. Trans. Amer. Inst. Min. Engrs., vol. 27, pp. 123–129. 1898. Jones, C. C. A geologic and economic survey of the clay deposits of the lower Hudson River Valley. Trans. Amer. Inst. Min. Engrs., vol. 29, pp. 40–83. 1900.

The methods of examination and estimate will depend chiefly on the origin, and consequently the form, of the clay deposit, whether a bed, a lens, or a steeply inclined mass. As to weights, long series of records justify the assumptions that ordinary soft clays will average 120 lbs. per cubic foot in the bank, and shales 150 lbs. per cubic foot. For rough calculations as to tonnage it may therefore be assumed that clays will weigh 1½ tons and shales 2 tons per cubic yard, in the bank.

List of references on clays and shales.—The literature of clays is so extensive that the descriptive papers in the following list have been arranged by States in alphabetical order.

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ALABAMA. Ries, H., and Smith, E. Preliminary report on the clays of Alabama. Bulletin 6, Alabama Geological Survey, 220 pp. 1900.

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MICHIGAN. Ries, H. Clays and shales of Michigan. Vol. 8, pt. 1. Reports Michigan Geological Survey, 67 pp. 1900.

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Slates.

Slate is, so far as origin is concerned, merely a form of shale in which a fine, even, and parallel cleavage has been developed by pressure. In composition, therefore, it will vary exactly as do the shales considered in the last section, and so far as composition alone is concerned, slate would not be worthy of more attention, as a Portland-cement material, than any other shale.

Commercial considerations in connection with the slate industry however, make slate a very important possible source of cement material. Good roofing slate is a relatively scarce material and commands a good price when found. In the preparation of roofing slate for the market so much material is lost during sawing, splitting, etc., that only about 10 to 25 per cent of the amount quarried is salable as slate. The remaining 75 to 90 per cent is of no service to the slate-miner. It is sent to the dump heap, and is a continual source of trouble and expense. This very material, however, as can be seen from the analyses quoted below, is often admirable for use in connection with limestone in a Portland-cement mixture. As it is a waste-product, it could be obtained very cheaply by the cement manufacturer.

Geographic distribution of slates.—The principal areas in the United States in which roofing slate is at present quarried are briefly noted below. For more detailed information on the subject, reference should be made to the papers and reports listed on page 336.

Beginning in the northeast, slates are extensively quarried in the Brownsville-Monson area in northern Maine, but no satisfactory limestones occur in this district. The next important slate area lies in western Vermont and eastern New York, a region well supplied with good limestones. In New Jersey and Pennsylvania slates are worked just north of the Lehigh cement-rock belt, as noted in Chapter XXI. The Peach Bottom slate district, located in southern Pennsylvania and northeastern Maryland, is also important, but is poorly supplied with limestone. Isolated slate districts occur in Virginia, but not near limestone areas. In eastern Tennessee and northwestern Georgia,

however, roofing slates and non-magnesian limestones occur in close proximity; and in the Georgia slate district a Portland-cement plant is already in operation. West of the Mississippi, good slates are worked more or less extensively in Minnesota, Arkansas, Utah, and California.

Composition of slates.—The composition of a large series of American roofing slates from various localities is given in Table 162.

TABLE 162.

ANALYSES OF AMERICAN ROOFING SLATES.

	1.	2.	3.	4.	5.	6.	7.
Silica (SiO_2)	54.24	56.42	60.80	67.70	67.76	59.84	67.61
Alumina (Al_2O_3)	24.71	24.14	22.00	13.49	14.12	15.02	13.20
Iron oxides (Fe_2O_3,FeO)	8.39	4.46	10.50	2.75	5.52	5.96	6.56
Lime (CaO)	5.23	0.52	0.50	0.81	0.63	2.20	0.11
Magnesia (MgO)	2.59	2.28	0.70	1.29	2.38	3.41	3.20
Alkalies	2.15	8.68	2.30	4.91	4.82	5.60	5.12
Water and CO_2	(?)	3.88	1.80	9.05	3.61	6.83	3.42

	8.	9.	10.	11.	12.	13.	14.
Silica (SiO_2)	56.49	68.62	55.88	58.37	62.71	60.65	58.20
Alumina (Al_2O_3)	11.59	12.68	21.85	21.98	19.40	16.87	18.83
Iron oxides (Fe_2O_3,FeO)	4.90	4.20	9.03	10.66	2.18	7.79	5.78
Lime (CaO)	5.11	2.34*	0.16	0.30	1.11	1.91	4.35
Magnesia (MgO)	6.43	3.76*	1.49	1.20	1.73	2.39	3.51
Alkalies	4.29	3.73	4.10	1.93	4.74	5.98	3.20
Water and CO_2	10.61	4.47	3.39	4.42	4.08	3.63	4.67

* Carbonate.

1, 2. Monson, Maine.
3. Lancaster, Mass.
4. Hamburg, N. Y.
5. West Pawlet, Vt.
6. Pawlet, Vt.
7. Poultenev, N. Y.
8. Raceville, N. Y.
9. Bangor, Pa.
10. Peach Bottom, Pa.–Md. belt.
11. Peach Bottom, Pa.–Md. belt.
12. Martinsburg, W. Va.
13. Arvonia, Va.
14. Rockmart, Ga.

TABLE 163.

COMPOSITION OF AMERICAN ROOFING SLATES.

	Maximum.	Average.	Minimum.
Silica (SiO_2)	68.62	60.64	54.05
Alumina (Al_2O_3)	24.71	18.05	9.77
Iron oxides (FeO,Fe_2O_3)	10.66	6.87	2.18
Lime (CaO)	5.23	1.54	0.00
Magnesia (MgO)	6.43	2.60	0.12
Alkalies (K_2O,Na_2O)	8.68	4.74	1.93
Ferrous sulphide (FeS_2)	.....	0.38	
Carbon dioxide (CO_2)	.....	1.47	
Water of combination	.....	3.51	
Moisture, below 110° C	.....	0.62	

Slates used in cement-manufacture.—Only one American Portland-cement plant has tried using roofing slate as one of its raw materials, and this plant is of quite recent construction. It is that of the Southern States Portland Cement Company, and is located about half a mile east of the village of Rockmart, Polk County, Ga.

Hard blue slates of Ordovician age, which have been extensively quarried for structural purposes, outcrop on the hills south of Rockmart. East of the town the surface rock is the "Chickamauga limestone," which here contains beds of pure non-magnesian limestone which have been quarried at several points for lime.

The cement company purchased the property of the old Georgia Slate Company, half a mile southwest of Rockmart. The intention was to quarry the slate, sell as slate the portions best suited for that use, and utilize the scrap and waste in the manufacture of cement.

TABLE 164.

ANALYSES OF SLATE USED FOR PORTLAND CEMENT, ROCKMART, GA.

	1.	2.
Silica (SiO_2)	57.40	58.20
Alumina (Al_2O_3)	23.65	18.83
Iron oxide (CaO)	4.45	5.78
Lime (CaO)	3.23	4.35
Magnesia (MgO)	3.23	3.51
Alkalies (K_2O,Na_2O)	n. d.	3.20
Sulphur (S)	n. d.	0.49
Carbon (C)	n. d.	0.82
Carbon dioxide (CO_2)	6.80	0.60
Water		4.07

1. J. F. Davis, analyst. Privately communicated.
2. Slocum and Vandeventer, analysts. 18th Ann. Rep. U. S. Geol. Survey, pt. 5.

References on slates.—The following papers contain material of interest in connection with the composition, distribution, and structure of slate.

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Coal Ash.

Among the other raw materials which are used to some extent in cement mixes, or which can be so used, may be mentioned iron ores (in the high-iron Portlands); bauxite (in the high-alumina Portlands); and coal ash in normal Portlands. The use of iron ore and of bauxite is briefly taken up on later pages (pages 517–519). The use of coal ash as a flux for over-siliceous clays and shales is a rather obvious economy, though not often practiced. On page 455 in table 192 will be found a larger number of coal-ash analyses than can be found elsewhere.

CHAPTER XXVI.

EXCAVATING THE RAW MATERIALS.

THE excavation of the raw materials is the first step toward the actual manufacture of Portland cement, and the one concerning which least has been published. Local conditions enter into this preliminary phase to such an extent that few general statements can be made concerning it. To a large extent, each separate deposit of raw material is an individual proposition to be handled best in a way peculiar to itself. The natural raw materials which are at present used in the American Portland-cement industry are worked by one of three general methods. These are: (1) quarrying or digging from open pits; (2) mining from underground workings, and (3) dredging from deposits covered by water.

Available excavation methods.—Disregarding dredging, which is of course a method usable only under certain clearly understood conditions, we may say that rock may be won by either quarrying or mining; and that in either case there are two subdivisions, according to the mode of attack or of transport. This gives four possible alternative methods of work. They are:

(1) *Quarrying;* in which all the work, both excavation and handling, is done in the open air. Of quarrying there are two broad subdivisions:
   (*a*) *Quarrying in benches or levels;* in which the working face of the quarry is carried up in step-like form.
   (*b*) *Quarrying with single face;* in which no benches are used, the stone being worked in a single straight and approximately vertical face.

(2) *Mining;* in which workings or handling take place underground. This has two broad subdivisions. Of mining methods there are:
   (*a*) *Underground mining proper;* in which all the work, both rock excavation and haulage, takes place under cover.

(*b*) *Pit-and-tunnel* or *Glory-hole* systems; in which the rock is excavated in the open air, but is milled down to a covered tunnel below the workings for loading and haulage.

These four methods of excavation have been named above in about the general order of their utility. Each of them has certain advantages and limitations, depending chiefly upon the character and structure of the rocks to be secured, but in part upon other features, topographic particularly.

The choice of methods.—The factors which influence the choice of methods, as between the different kinds of quarrying and mining work, are of various character; they include considerations of relative cost, of attitude on the rock beds, of the character of the bedding and of the individual beds, and of the surrounding topography. The effect of these different factors upon the choice of excavation methods may be briefly summarized as follows:

A. Cost.—Since we are interested in securing the necessary supply of rock at the lowest possible unit cost (and of proper composition), the relative cost of the four different methods is a matter of serious importance, though it is sometimes overborne by other considerations. As regards cost, we may say that quarrying is cheaper than mining, other things being equal, both in the first cost of installation and in the actual operation afterwards. But in each case there is a considerable difference at one or the other stages of the work, between the two sub-methods of each group. The four methods may be placed as follows, in the order of cheapness:

Cost of Installation.	Cost of Operation.
1, 2. Either quarry method; about equal in economy of first cost.	1. Quarry with single face.
	2. Quarry in benches.
3. Underground mining proper.	3. Pit and tunnel.
4. Pit-and-tunnel or glory-hole system.	4. Underground mining.

The above notes as to relative costs are based on the theory that in each case conditions permit the system chosen to be worked to its maximum of efficiency; in that case the choice would of course be determined by cost alone, and in that case we would obviously always work quarries, and always work them in single faces. But in real life the rocks do not give us such simple opportunities for choice. The other considerations, which often are so strong, in any particular case, as to overrule questions of cost, are related to the character and the position of the desirable rock-beds.

B. Rock conditions.—These various considerations may be summarized in so far as they affect each of the possible excavation methods, as follows.

Quarrying single face is economical always when the rock is massive or contains no large amount of undesirable beds. In the cement-rock quarries of Pennsylvania, in practically all shale quarries or clay pits, and in many of the better limestone quarries all of the material is usable, and in such cases deep drilling, heavy blasting, and single-face working are obviously the cheapest modes of attack.

Quarrying in benches always costs a little more, and sometimes much more, than quarrying single face. But it is necessary when the rock series contains beds of dangerous or undesirable character, at least to any serious extent. The actual quarry whose section is shown in Fig. 71 must clearly be worked in benches; when the stripping (Beds *A*–*C*) gets too thick it will indeed have to be mined underground, under cover of the good sandstone roof *C*, that is available, in order to get the desirable limestone and shale beds *D*, *E* and *F*.

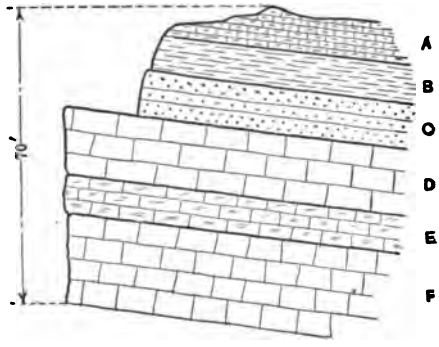


FIG. 71.—Actual cement quarry; typically adapted to working in benches at first, and later mining.

So long as the rocks are lying flat or nearly so, it is possible to extract pretty cheap rock by benching even from a badly mixed series of good and bad beds. But when the rocks are steeply tilted benching does not work well; in that case, if it is absolutely necessary to work the quarry, mining seems the better choice.

Underground mining can be carried out on beds ranging from 5 to 30 feet thick, and if the roof be good the expense is not prohibitive. It is in fact the only method applicable when a good desirable bed goes under cover too heavy to strip, so long as there is a good roof rock available. (Fig. 72.)

Pit-and-tunnel or **glory-hole** workings have long been employed in iron and other metal mines; their application to stone extraction is more recent and very limited. They require heavy preparatory work before any yield is obtained; they can be worked, after completion of the installation, very cheaply under favorable conditions. When the rock

sought for is a very heavy bed or mass, reaching the surface with little or no stripping, and when the outcrop is high above the mill level, the

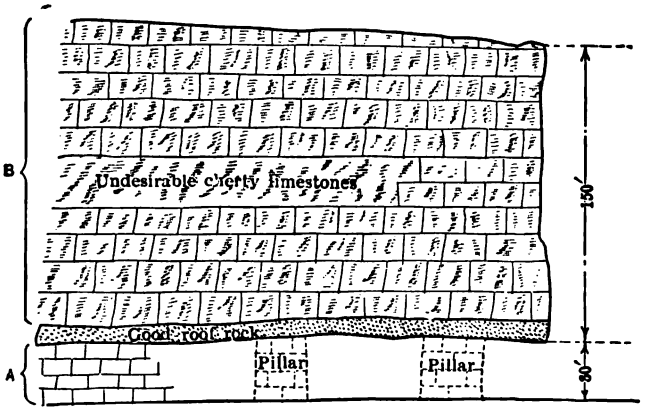


FIG. 72.—Limestone mine at Le Teil, France.

conditions for pit-and tunnel extraction are at their best. In Fig. 73 a layout of this favorable type is indicated in section.

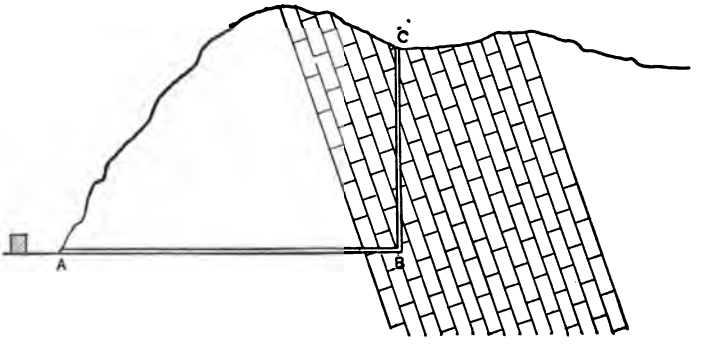


FIG. 73.—Ideal conditions for glory-hole system in limestone.

The three different general methods of excavation will first be briefly considered, after which the cost of excavating various raw materials will be discussed in some detail.

Quarrying.

In the following pages the term " quarrying " will be used to cover all methods of obtaining raw materials from open excavations—quarries, cuts, or pits—whether the material excavated be a limestone, a shale,

or a clay. Quarrying is the most natural and common method of excavating the raw materials for cement-manufacture. If marl, which is usually worked by dredging, be excluded from consideration, it is probably within safe limits to say that 95 per cent of the raw materials used at American Portland-cement plants are obtained by quarrying. If marls be included, the percentages excavated by the different methods would probably be about as follows: quarrying, 92 per cent; dredging, 6 per cent; mining, 2 per cent.

Stripping.—When a limestone is being quarried, the opening should be so located as to give as little stripping as possible in proportion to the available rock; for in this case the stripping is merely dead work, adding greatly to the expense of the product. In dealing with a shale-bed, the "stripping" is usually merely weathered shale and can be used as well as the harder portions of the deposit.

A very thick bed of limestone, or a bed of moderate thickness lying almost horizontally, will not give as much stripping per ton of good rock as a thin bed or a bed dipping at a high angle. In handling comparatively thin earth stripping in flat country, scrapers or excavators may be used; while at one cement-plant a heavy soil cover on a quarry near a river-bank is removed by hydraulicking. This last process is also used in several large brick-plants.

Quarrying single-face.—The largest individual limestone quarries in the country are single-face quarries, but they are not so numerous as bench quarries, a fact that is often overlooked. A single-face quarry, to be run at maximum economy, should be in a rock series that does not contain many or thick beds of rock undesirable because of magnesia or otherwise. Given a thick series of good stone, a single-face quarry can be operated very cheaply; and it has the further advantage that it can handle steeply dipping beds more easily than any other mode of attack.

Single-face work permits the use of deep drill-holes and heavy single blasts. It thus overcomes one of the serious practical difficulties of a bench operation—the necessity for constant shifting of the loading tracks, and it permits the operation of steam shovels in really economical fashion. It is rarely realized how much of the possible efficiency of a shovel is lost in ordinary practice through delays and shifts of position.

Quarry in benches.—In most of the quarries for cement rock or limestone, the rock is opened up on a low side-hill, so as to give a long working-face with light stripping and as little grade as possible in the workings. The rock is blasted down in one or more benches, according to the height of face exposed, and the larger pieces are sledged or reblasted

FIG. 74.—View of typical quarry.

FIG. 75.—Temporary tracks laid to face.

to manageable size by men placed along the working-face. It is then loaded either into one-horse carts or into small cars running on temporary tracks laid close up to the face. In the former case the carts are driven to a dump and loaded into cars; in the latter case the cars are drawn by horses or pushed by men to a turntable. This turntable is a comparatively fixed affair, located far enough away from the working face to avoid damage from blasting. Here the cars are attached to a cable or to a locomotive and hauled to the mill.

FIG. 76.—Cableway in cement-rock quarry.

Occasionally an aerial cableway is used for transporting the material to the mill. This is shown in the view of a cement-rock quarry given in Fig. 76.

In quarries containing several beds of rock differing greatly in composition and lying horizontally, tracks are often run in on different levels, so as to insure that each car or cart shall contain only one kind of rock. This practice is exemplified in the shale-pit shown in Fig. 77. A similar plan is followed in working the quarry partly shown in Fig. 78, which contains several heavy beds of limestone intercalated with workable but thinner layers of shale.

FIG. 77.—Shale-pit worked in two levels.

FIG. 78.—Hoisting from quarry worked in levels.

Use of steam-shovels.—In many limestone and cement-rock quarries a steam-shovel is employed to load the blasted rock into the cars, and in shale quarries this use of steam-shovels is more frequent. In certain clay- and shale-pits, where the material is of suitable character, the steam-shovel can be employed to do all the work, both excavating and loading the materials.

Steam-shovels are in use at the plant of the Purington Paving Brick Company, at Galesburg, Ill. Here a bank of firm shale is drilled, shaken with black powder, and then handled entirely by steam-shovel. The following detailed figures of cost have been recently published by Mr. C. W. Purington.

The figures cover the handling of 17,422 cubic yards of shale in one month of twenty-six nine-hour days. This shale was dug from a 50-foot bank with a Model 90 Barnhart shovel with 2-yard dipper. It was delivered to twenty 2-yard cars and trammed in two directions (1500 to 2000 feet respectively) to the bottoms of two inclines. It was then hoisted by cable to hoppers placed at an elevation of 20 feet above the track and dumped into the hoppers.

TABLE 165.

DETAILED COSTS OF STEAM-SHOVEL WORK. (PURINGTON.) 1903.

		Per Month.	Per Yard, Cents.
Labor	1 engineer on shovel	$110.00	
	1 craneman	85.00	
	1 fireman at 22½ cents per hour	52.65	
	3 trackmen at 17½ cents per hour	128.85	
	1 engineer on locomotive	80.00	
	1 switchman at 20 cents per hour	46.80	
	2 hoistmen at 20 cents per hour	93.60	
	Total labor	$596.90	0.0343
Fuel	1½ tons coal per day at $2.00 per ton for shovel	78.00	
	½ ton coal per day at $2.00 per ton for locomotive	26.00	
	1 ton coal per day at $2.00 per ton for two hoists	52.00	
	Total fuel	$156.00	0.0089
	Total costs, labor and fuel	$752.90	0.0432

These figures do not include charges for superintendence, oil, waste, etc. If these be included, the cost of the steam-shovel work will be about 5 cents per cubic yard. If the cost of drilling and blasting be added, the total cost of handling the shale from the bank to the hoppers may be about 6 cents per cubic yard. Of this the blasting dig-

ging, etc., amounts to about 4 cents per yard, while the tramming, hoisting, and dumping will amount to the remaining 2 cents.

In handling shales, steam-shovels are usually very effective excavators, for here the material is physically homogeneous and requires only one light blasting to break it into fragments that can be readily handled by the shovel. This is well brought out by the itemized costs given above for the Galesburg shale quarry.

When dealing with limestones, local conditions may decrease the effectiveness of the shovel, and in many quarries will entirely prevent its use. In shallow quarries vertical seams filled with clay, soil, or other wash from the surface may greatly hinder the work of the shovel; and in quarries where rock is so mixed in composition as to require sorting the shovel is worse than useless.

Crushing and drying in the quarry.—The rock is usually transported directly to the mill just as quarried, except that the larger masses are sledged to convenient size for handling. At a few quarries, however, a crushing-plant is installed at the quarry, and the rock is sent as crushed stone to the mill. Several of the quarries in question sell a certain portion of their product as road metal, which, of course, reduces the cost of the finer material which is sent to the cement-plant.

A few plants have also installed their driers at the quarry and dry the stone before shipping it to the mill. This practice shows a saving in mill space, but otherwise it seems to have little to recommend it. In the cases where a wet clay or shale is quarried some distance away from the mill the saving in transportation charges, due to drying at the quarry, would, of course, be considerable.

Mining.

The term " mining " will be used, in distinction from " quarrying," to cover methods of obtaining any kind of raw material by underground workings, through shafts or tunnels. Mining is rarely employed in excavating materials of such low value per ton as the raw materials for Portland-cement manufacture. Occasionally, however, when a thin bed of limestone or shale is being worked, its dip will carry it under such a thickness of other strata as to make mining cheaper than stripping and quarrying for that particular case.

Mining is considerably more expensive work than quarrying, but there are a few advantages about it that serve to counterbalance the greater cost per ton of raw material. A mine can be worked steadily and economically in all kinds of weather, while an open cut or quarry

is commonly in a more or less unworkable condition for about three months of the year. Material won by mining is, moreover, always dry and clean.

Underground mining is practicable economically when (1) the desir-

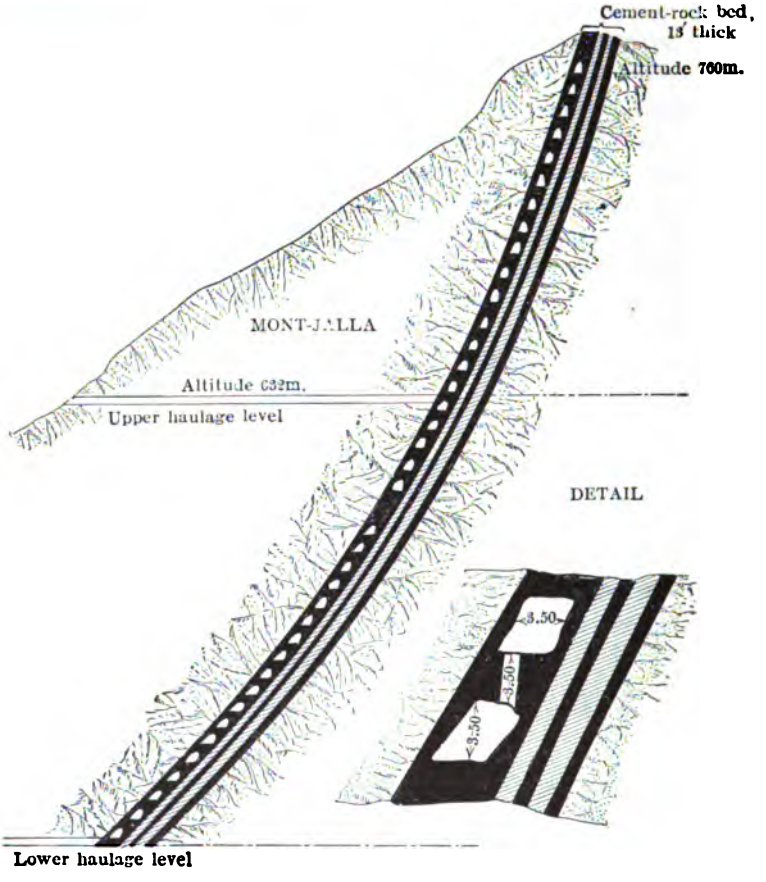


FIG. 79.—Cement-rock mines at Grenoble, France. Almost ideal conditions for milling through chutes to low haulage level, with maximum stopping space feeding to this level.

able rock occurs in a bed from 8 to 30 feet thick; lying flat or slightly inclined, and with a good solid roof-rock overlying the desirable stone. A good example of conditions justifying and even necessitating mining for cement stone is afforded by the mine shown in section on Fig. 79.

Pit-and-tunnel systems, including the methods which are called

"glory-hole" and "milling," are of use under certain very definite conditions. There must be a large mass of the desirable rock; it must be pretty free from any undesirable beds or layers; and it must be located topographically so as to be obtainable by pit-and-tunnel methods. This last implies that the rock must outcrop well above the level of the mill or shipping level. It also implies that there is some natural obstacle, or a property line, between rock and mill or else, under such conditions, a great single-face quarry would be employed. In Fig. 73 the ideal conditions for a glory-hole proposition are indicated. It will be seen that they require unusual advantages. The entry tunnel *A–B* which must be driven through dead rock before a ton can be taken, can not be too long; it is a matter which may cost $10 to $20 per foot of advance. The raise or shaft driven to the surface (*B–C*) is ordinarily in good rock throughout, but that helps out very little in the first costs. After it is once installed, however, working costs are of course very low. The rock is blasted down in a basin around the shaft mouth *C*, and milled down through the shaft to the tunnel. Here it is fed through gates into cars. What we gain by this method, which has been long practiced in mining work, is to keep the loading head fixed, as against the perpetually shifting positions of a quarry face. The only serious operating troubles come from ore sticking in the chutes; that is due in part to overloading, in part to natural stickiness (in some ores and rocks); in part to freezing (in some climates).

The costs are low as soon as operations can begin; they may fall to ten to twenty cents a ton, for actual working costs. But when interest and amortization on first cost are added, the comparison with quarry work is not so one-sided. It is worth noting, also, that the costs of glory-hole mining reach their minimum very soon after first shipments begin, and that they tend to increase slightly rather than decrease after that.

Dredging.

The term "dredging" will be here used to cover all methods of excavating soft, wet, raw materials. The fact that the materials are wet implies that the deposit occurs in a basin or depression, and this in turn implies that the mill is probably located at a higher elevation than the deposit of raw material, thus necessitating uphill transportation to the mill.

The only raw material for Portland-cement manufacture that is extensively worked by dredging in the United States is marl. Occasionally the clay used is obtained from deposits overlain by more or

less water; but this is rarely done except where the marl and clay are interbedded or associated in the same deposit.

A marl deposit, in addition to containing much water diffused throughout its mass, is usually covered by a more or less considerable depth of water. This will frequently require the partial draining of the basin in order to get tracks laid near enough to be of service.

In dredging marl the excavator is frequently mounted on a barge which floats in a channel resulting from previous investigation. Occa-

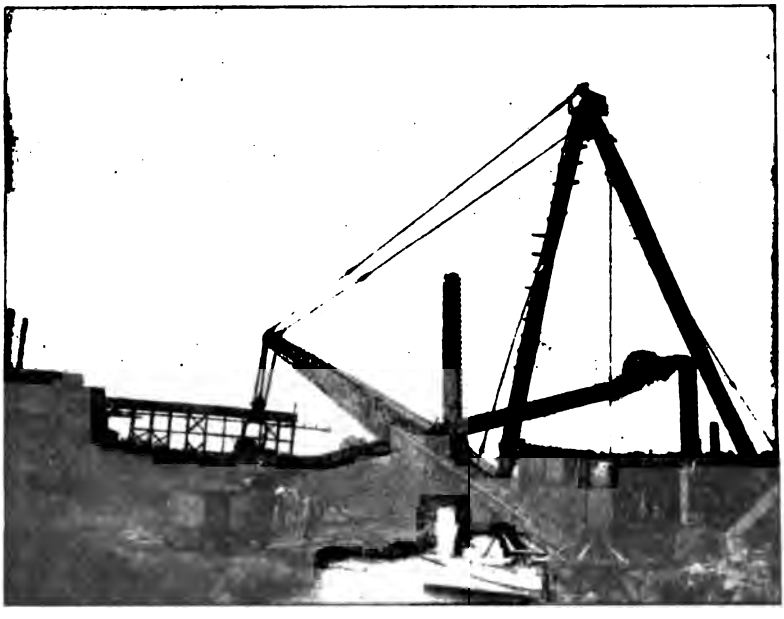


FIG. 80.—Dredge at marl-plant.

sionally, in deposits which either were originally covered by very little water or have been drained, the shovel is mounted on a car running on tracks laid along the edge of the deposit.

The material brought up to the dredge may be transported to the mill in two different ways, the choice depending largely upon the manufacturing processes in use at the plant. At plants using dome or chamber kilns, or where the marl is to be dried before sending to the kiln, the excavated marl is usually loaded by the shovel on cars and hauled to the mill by horse or steam power. At normal marl-plants using a very wet mixture it is probable that the second method of transpor-

tation is more economical. This consists of dumping the marl from the excavator into tanks, adding sufficient water to make it flow readily, and pumping the fluid mixture to the mill in pipes.

Marl-pumping.—The following description of the Harris system of pumping marl from the lake to the mill is taken from the catalogue of the Allis-Chalmers Company:

"This method of handling marl by compressed air is now in great favor, and many plants have been and are now being installed in cement works in this country and Canada.

"The essential features are given in the diagram herewith, and comprise the pump-tanks, air-compressor, automatic switch, and piping. There are no floats. There are no air-valves outside the engine-room.

"The air is not allowed to escape after doing its work. The expansive force of the air is used in the compression cylinder of the compressor, thus giving back the greater part of its energy to the compressor.

"Suppose the compressor to be in operation with switch set as in the figure, the air will be drawn out of the right-hand tank and forced into the left-hand tank, and in so doing will draw marl into the former and force it out of the latter.

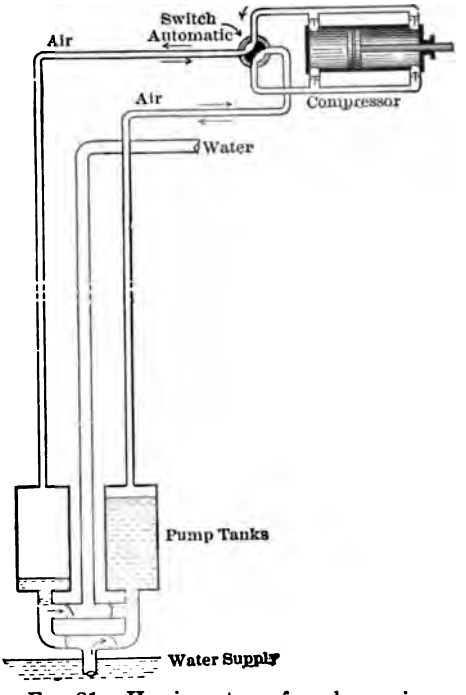


FIG. 81.—Harris system of marl-pumping.

"The charge of air in the system is so adjusted that when one tank is emptied the other is just filled. At that moment the switch will reverse the pipe connections so that action in the tanks will be reversed.

"The switch is adjustable and can be set or regulated while the pump is in operation."

For further data, reference should be made to a paper by E. G. Harris, published in "Mines and Minerals," vol. 15, pp. 513–514. May, 1905.

Costs of Raw Material Excavation.

It will be convenient to divide this subject, according to classes of raw material and methods employed into (1) quarrying for limestone or cement rock; (2) quarrying shale and clay and (3) dredging marl. This last is a matter which was formerly of great importance in the United States and Canada, but it is yearly becoming less important to the cement industry. The data on it presented in the first edition of this book have therefore been allowed to stand unchanged, while, as regards limestone and shale quarrying the sections on costs have been entirely rewritten in the light of recent and very complete information. The costs in all cases have been retained on the 1900–1915 price level, the reasons for this action being stated on pages 6 and 8.

Quarrying limestone, etc.—Quarry costs vary not only from quarry to quarry, but from month to month in the same quarry, so that to get any results of value for comparison long periods have to be considered, and exceptional quarries eliminated.

Examination of cost sheets covering in each case a year or more of normal operation, for twelve mills of varying size, some moderate, others very large, gave results as follows for the period 1913–1915. The actual quarry costs ranged from 17.44 cents per ton to 53.16 cents per ton of stone, delivered either at the mill or at a main-line railroad point. (The reason for this distinction is that I wished to eliminate some examples of very heavy freight charges, which are unfortunate for the mills concerned but have really nothing to do with the question of quarrying costs.) The average of all these examples was 37.66 cents per ton of limestone. If the average were weighted according to size of mill it would not be seriously changed, for one of the very largest producers had a high cost. The mills included in this summary are very widely scattered over the United States east of the Rockies, and the stone worked in their quarries shows every possible variation as to thickness, hardness and stripping.

I may note that so far as shallow quarries are concerned the stripping is the chief factor in variations in cost. In the deeper quarries the chief differences seem to arise from differences in the haulage. The items concerned with the actual rock-breaking are comparatively uniform throughout.

Quarrying shale and clay.—There is far less important variation in shale- and clay-pit costs throughout the country than in the limestone quarries that have just been discussed. A group of very typical cost sheets over long periods ranged, a few extraordinary instances being

excluded, between 20 and 30 cents per ton of shale for quarrying and delivering at nearby mills. In this connection I may note that, since most cement plants were originally located with regard to their limestone holdings, there is a tendency to find higher freight charges on shale than on the stone. As compared with limestone quarries, shale pits normally show very low items for powder and supplies; the labor item varies largely with the amount of use made of the steam shovels. In clay pits especially the variations from month to month in the same pit are often enormous; that is chiefly caused by weather conditions, which exert their maximum influence on clay banks.

Cost of marl-dredging.—The costs of dredging and handling marl at several American cement-plants are given below on 1900–1915 base.

The figures given are correct enough so far as actual operation is concerned; but the percentage of lost time in a marl operation, due to weather or other conditions, adds greatly to the low costs of good periods.

Plant 1. The marl- and clay-pits are about 3½ miles by track from the mill. Both materials are covered by ½ to 1 foot of earth, but no water. A long cut is made into the deposit, into which cut cars are run on light tracks. These cars, containing about 3000 lbs. of marl, are loaded by hand. The contract price for loading is 8 cents per car for marl and 14 cents per car for clay, and these prices are equivalent to a pay of $3.00 to $4.00 per day of 12 hours for each laborer loading. Two engines are used, one for switching and making up trains at the marl- and clay-pits, the other for hauling the trains to the mill. The total cost for sufficient marl and clay for 1200 barrels cement is:

2 engineers at $1.50	$3.00
2 firemen at $1.25	2.50
400 cars marl at $0.08	32.00
80 cars clay at $0.14	11.20
2000 lbs. coal at $2.40 per ton	2.40
Total cost marl and clay for 1200 bbls. cement	$51.10
Cost marl and clay for 1 bbl. cement	0.043

Plant 2. The marl and clay occur in a swamp half a mile from the mill. The surface material is 2 to 3 feet black loam; this is underlain by 9 feet marl, and this, in turn, by the clay. A dredge with a 15-H.P. engine and a crew of two men handles the marl, digging enough for 240 barrels cement in ten hours. A smaller dredge with orange-peel bucket, run by one man, handles the clay. One locomotive hauls the material to the plant over tracks laid alongside the excavations. Total costs per day for a 240-barrel plant are as follows:

1 marl-dredge runner	$1.50
1 leverman, marl dredge	1.25
1 clay-dredge runner	1.25
1 locomotive engineer	1.50
350 lbs. coal for marl dredge at $2.20 per ton	0.38½
150 lbs. coal for clay dredge at $2.20 per ton	0.16½
500 lbs. coal for locomotive at $2.20 per ton	0.55
Cost of clay and marl for 240 barrels cement	$6.50
Cost of clay and marl for 1 barrel cement	0.027

Plant 3. Marl dredged from lake one-quarter mile from mill. This is done by contract, the marl being delivered to the mill for 5¼ cents per cubic yard. This price is about equivalent to $0.018 per barrel of cement *for marl alone.* In this case the dredging-plant was bought and installed at the expense of the company, but the contractor pays all the current expenses, including pay, repairs, coal, etc.

Plant 4. Marl dredged from lake one-third mile from mill by a dredge operating a 1½-cubic yard orange-peel bucket. The marl is fed through a stone separator and then pumped to the mill on Harris system. Total cost is about as follows:

2 men at $1.50	$3.00
3 men at $1.25	3.75
2½ tons coal at $2.40	6.00
Total cost of marl for 500 barrels cement	$12.75
Cost of marl for 1 barrel cement	0.025

Cost of Raw Materials at Mill.

The most natural way, perhaps, to express the cost of the raw materials delivered at the mill would be to state it as being so many cents per ton or cubic yard of raw material; and this is the method followed by quarrymen or miners in general. To the cement manufacturer, however, such an estimate is not so suitable as one based on the cost of raw materials per ton or barrel of finished cement.

Loss on drying, etc.—In the case of hard and comparatively dry limestones or shales, it may be considered that the raw mixture loses 33⅓ per cent in weight on burning. Converting this relation into pounds of raw material and of clinker, we find that 600 pounds of dry raw material will make about 400 pounds of clinker. Allowing something for other losses in the process of manufacture, it is convenient and sufficiently accurate to estimate that 600 pounds of dry raw material will give one barrel of finished cement. These estimates must be increased if the raw materials carry any appreciable amount of water. Clays will frequently contain 15 per cent or more of water; while soft, chalky

limestones, if quarried during wet weather, may carry as high as 15 to 20 per cent. A Portland-cement mixture composed of a pure chalky limestone and a clay might, therefore, average 10 to 20 per cent of water, and consequently about 700 pounds of such a mixture would be required to make one barrel of finished cement.

With marls the loss on drying and burning is much greater. Russell states that according to determinations made by E. D. Campbell, 1 cubic foot of marl as it usually occurs in the natural deposits contains about 47½ lbs. of lime carbonate and 48 lbs. of water. In making cement from a mixture of marl and clay, therefore, it would be necessary to figure on excavating and transporting over 1000 lbs. of raw material for every barrel of finished cement.

From the preceding notes it will be understood that the cost of raw materials at the mill per barrel of cement will vary not only with the cost of excavation, but with the kind of materials in use.

Actual costs at mills.—In the first edition of this book it was noted (p. 378) that "In dealing with hard, dry raw materials extracted from open quarries near the mills, the cost of raw materials may vary between 8 cents and 15 cents per barrel of cement. The lower figure named is probably about the lowest attainable with good management and under favorable natural conditions; the higher figure is probably a maximum for fairly careful management of a difficult quarry under Eastern labor conditions."

Recalling that we are purposely quoting costs on a 1900–1915 base level, that statement needs little revision; there are examples of lower costs than 8 cents per barrel, but there are also examples of considerably higher costs than 15 cents, and this last class includes some very important mills. The following table gives details as to raw material costs at a number of mills, varying from moderate to very large size, during the period 1913–1915.

TABLE 166.

ACTUAL COSTS OF RAW MATERIALS AT TYPICAL MILLS.

Mill.	Limey Component.			Clayey Component.			Total Raw Mix.	
	Cost, Cents per Ton.	Pounds Used per Barrel.	Cost, Cents per Barrel.	Cost, Cents per Ton.	Pounds Used per Barrel.	Cost, Cents per Barrel.	Pounds Used per Barrel.	Cost, Cents per Barrel.
A	23.32	649	7.57	....	....	....	649	7.57
B	39.84	492	9.80	29.00	114	1.65	606	11.45
C	17.44	494	4.31	23.33	128	1.49	622	5.80
D	67.35	606	20.41	x	x	0.78	626	21.19
E	54.55	536	14.62	61.07	89	2.73	625	17.35
F	39.53	428	8.45	27.96	154	2.16	582	10.61

CHAPTER XXVII.

CALCULATION AND CONTROL OF THE MIX.

If, as in the present volume, we exclude from consideration the so-called "natural Portlands" (see page 214), Portland cement may be regarded as being entirely an artificial product, obtained by burning to semi-fusion an intimate mixture of pulverized materials, this mixture containing lime, silica, and alumina varying in proportion only within certain narrow limits, and by crushing finely the clinker resulting from this burning.

If this restricted definition of Portland cement be accepted, four points may be regarded as being of cardinal importance in its manufacture. These are:

1. The cement mixture must be of the proper chemical composition.
2. The materials of which it is composed must be carefully ground and intimately mixed before burning in order to insure that chemical combination shall take place after calcination.
3. The burning must be conducted at the proper temperature, which varies considerably according to the chemical composition of the mixture, and the length of time during which it is subjected to the burning process.
4. After burning, the resulting clinker must be finely ground.

In this and the succeeding chapters these points will be taken up separately and in some detail.

The present chapter deals with the calculations and arrangements necessary for insuring the correctness of the cement mixture. It, therefore, includes discussions of the theoretical and practical considerations which determine the proportions of the mixture. Among these considerations are the theoretical composition and constitution of Portland cement; the influence of various normal constituents on the properties of the mixture; the influence of fuel ash and other accidental impurities; and the methods of calculating and controlling the mix in actual practice.

Theoretical Composition of Portland Cement.

During recent years much attention has been paid by various investigators to the constitution of Portland cement. The chemical composition of any particular sample can, of course, be readily determined by analysis, and by comparison of a number of such analyses, general statements can be framed as to the range in composition of good Portland cements. This subject is discussed further in Chapter XXXVI, where a large number of analyses are presented.

Chemical analyses will determine what ingredients are present, and in what percentages, but other methods of investigation are necessary to ascertain in what manner these ingredients are combined. A summary of the more important practical results brought out by these investigations on the constitution of Portland cement will be given in the present chapter, while in Chapter XXXVI a more detailed discussion of the problem will be presented, as well as references to the principal papers on the subject.

It would seem to be firmly established that in a well-burned Portland cement much of the lime is combined with most of the silica to form the compound $3CaCO,SiO_2$,—tricalcic silicate. To this compound is ascribed, in large measure, the hydraulic properties of the cement; and in general it may be said that the value of a Portland cement increases directly as the proportion of $3CaO,SiO_2$. The ideal Portland cement, toward which cements as actually made tend in composition, would consist exclusively of tricalcic silicate, and would be therefore composed entirely of lime and silica in the following proportions:

Lime (CaO)	73.6
Silica (SiO_2)	26.4

Such an ideal cement, however, cannot be manufactured under present commercial conditions, for the heat required to clinker such a mixture cannot be attained in any working kiln. The oxyhydrogen blowpipe and the electrical furnace will give clinker of this composition; but a pure lime-silica Portland is not possible under present conditions as to burning and grinding on a commercial scale.

In order to prepare Portland cement in actual practice, therefore, it is necessary that some other ingredient or ingredients should be present to serve as a flux in aiding the combination of the lime and silica, and such aid is afforded by the presence of alumina and iron oxide.

Alumina (Al_2O_3) and iron oxide (Fe_2O_3) when present in noticeable percentages serve to reduce the temperature at which combina-

tion of the lime and silica (to form $3Ca,SiO_2$) takes place; and this clinkering temperature becomes further and further lowered as the percentages of alumina and iron are increased. The strength and value of the product, however, also decrease as the alumina and iron increase; so that in actual practice it is necessary to strike a balance between the advantage of low clinkering temperature and the disadvantage of weak cement, and to thus determine how much alumina and iron should be used in the mixture. This point will be further discussed on later pages.

It is generally considered that whatever alumina is present in the cement is combined with part of the lime to form the compound $3CaO,Al_2O_3$—tricalcic aluminate. The occurrence of lower aluminates, however, is at least possible, and the condition of the iron—whether entirely as lime ferrite or in part as ferric silicate, is undetermined. These questions as to constitution are discussed in Chapter XXXVI. In the relatively small percentages in which iron occurs in Portland cement it may for convenience be considered as approximately equivalent to alumina in its action.

Influence of Normal Constituents on the Cement.

Lime, silica, alumina, iron oxide, magnesia, sulphur, and alkalies may be regarded as being normal constituents of any Portland-cement mixture. The three first named are necessary ingredients, while the last two, though undesirable, are rarely entirely absent from the raw materials used. The influence exerted by greater or lesser proportions of these seven constituents on the properties of both mixture and finished cement will be discussed in the present chapter.

Maximum lime content of mixture.—On pages 366–367 Newberry's method of proportioning cement mixtures will be described and exemplified. It should be borne in mind, however, that the Newberry formula there quoted will, if followed, give the *maximum* lime content that the mixture could bear, *providing* that the grinding, mixing, and calcination were performed with absolute perfection. As a matter of fact, however, the lime content of the mixture should never be carried quite as high as the formula would indicate, for in actual practice the mixing, grinding, and calcination are never theoretically perfect, and in consequence of a perfect combination of all the lime with all the silica and alumina cannot be attained. There will always remain a certain amount of uncombined material. If, therefore, the lime in

the mixture is carried as high as is theoretically allowable, a certain amount of free lime will occur in the cement. If, on the other hand, the mixture carries less than its proper theoretical percentage of lime, the cement will, of course, contain some uncombined silica or alumina or very acid compounds. A choice must be made, therefore, between the possibilities of having free lime in the product and having low-limed compounds. This choice is simple, for the effects on the value of the cement of these two possibilities are very different. Free lime is positively dangerous to the cement, while low lime compounds are less harmful, their only effect being to lower the tensile strength of the product. For this reason, since in practice it is necessary to choose between the two contingencies (free lime *vs.* free silica and alumina), the lime content of the mixture is always carried lower than theoretical considerations demand.

It is to be further noted in this connection that the lime content of Portland cements relatively high in silica may be carried higher than in the case of the more aluminous Portlands. In discussing the constitution of Portland cement in preceding paragraphs it was stated that though lime combines with both silica and alumina, the combining proportions are very different in the two cases. With silica, lime forms the tricalcic silicate, whose percentage composition is lime 73.6 per cent, silica 26.4 per cent; the lime and silica are therefore combined in the proportion of lime 2.8 to silica 1. With alumina and iron oxide the compounds formed by the lime are less definitely established; but they seem to be on the whole less basic than the typical lime-silica compound. It is evident, therefore, that a mixture containing 20 per cent silica and 5 per cent alumina can safely carry more lime than one containing 15 per cent silica and 10 per cent alumina.

Since the combination of lime, silica, and alumina becomes more thorough in proportion as the mixing, grinding, and burning are better done, higher lime contents can be carried by carefully prepared mixtures than by careless or coarsely ground mixtures; and in rotary-kiln plants lime may be carried higher than in those using dome kilns.

Up to the limit of safety every increase in the percentage of lime in the mixture will cause, other things being equal, an increase in the strength of the cement. This fact is taken advantage of, particularly when a new brand is being placed on the market. The usual method of procedure at such a time is to carry the lime very high, burn very hard, and pulverize very fine. This makes a costly but high-testing cement. As soon as the brand has become well established, the lime content can be dropped to reasonable working limits.

Minimum lime content of mixture.—The maximum lime content of the mixture is fixed by the considerations set forth in the preceding paragraphs. The minimum lime content, however, will also require some consideration. Low lime will invariably mean low-testing cements, and in the present state of the industry, low-testing cements are not easily marketed. A low-lime content is also the cause, in part, of the "dusting" of clinker in the vertical kiln. Le Chatelier found that the dicalcic silicate ($2CaO,SiO_2$) possesses the property of spontaneously disintegrating on cooling. If the lime content of the mixture be carried too low, therefore, the clinker will fall to dust in the kiln, owing to the production of this unstable dicalcic silicate.

Magnesia.—The question as to the percentage of magnesia allowable in a Portland cement has given rise to serious controversy for many years. In Europe the tendency has been to keep it below 3 per cent; but in this country, largely because of the results attained by Lehigh Valley cements above this limit, 4 or 5 per cent has been considered the allowable maximum. All this discussion was carried on under the idea that magnesia was either inert or positively harmful in a Portland cement.

Recent experiments by Prof. Newberry, however, have proven that an entirely satisfactory cement can be made carrying as high as 10 per cent of magnesia, if due care be given to the mixing and burning. This might have been expected, both on theoretical grounds and because of the evidently active nature of magnesia in even the highest-burned natural cements, as pointed out on pages 206–207. At present it seems safe to say that magnesia can be considered equivalent to lime in its action, if due allowance be made for the difference in their combining weights. It is therefore theoretically possible to prepare a series of lime-magnesia Portlands, parallel to our present lime Portlands; and it is probable enough that in a few years some move will be made in this direction. But it must be borne in mind that a lime-magnesia Portland will probably differ in important respects from our present lime Portlands, and that it will therefore be inadvisable to group the two types of cement under the same general name. For this reason, in the present volume, the term Portland has been restricted by definition to apply only to cements carrying less than 5 per cent of magnesia (MgO).

Silica.—It is commonly considered that the ultimate strength of the cement depends in large part upon the amount of calcium trisilicate it contains. Within certain limits, therefore, any increase in the percentage of silica in the mixture will increase the strength of the cement.

On the other hand, an increase in silica will usually imply a decrease in alumina and iron oxide, and this in turn will cause the cement to be slow-setting (which is an advantage), but hard to clinker.

Alumina.—To the calcium aluminate of a cement are ascribed the initial setting properties. Decrease in the alumina, therefore, tends to make the cement slower setting, while high alumina affects it in the opposite way. Though it is advisable to carry the alumina as low as possible, so as to secure slowness of set and greater ultimate strength, it is impossible to carry it below a certain minimum, for alumina aids greatly in securing a low clinkering temperature, and a cement very low in alumina will clinker only with great difficulty. Too much alumina, on the other hand, will give a very fusible and sticky clinker, liable to ball in the kiln.

Le Chatelier considers that the aluminous compounds present in Portland cement are the direct cause of its destruction by sea-water. His theory to account for this disintegration is as follows: Free lime, liberated during the hardening of the cement, reacts with the magnesium sulphate always present in sea-water, to form calcium sulphate. This in turn reacts with the calcium aluminate of the cement to form a sulphaluminate of lime, which swells considerably on hydration and thus disintegrates the cement mass. The extent of the disintegration varies directly with the percentage of alumina present in the cement. Cements containing 1 or 2 per cent of alumina are, for example, practically unaffected by sea-water, while in cements containing as high as 7 or 8 per cent of alumina the swelling and consequent disintegration are very rapid.

If the alumina of a cement be replaced by an oxide not reacting with calcium sulphate, the stability of the cement in sea-water is greatly improved. Le Chatelier has demonstrated this by preparing cements in which the alumina was replaced by oxides of iron, chromium, cobalt, etc. All of these were more resistant than an alumina cement to the disintegrating effect of lime sulphate. The best effects were obtained when iron oxide was used, a cement corresponding in composition to $5SiO_2,Fe_2O_3,17CaO$ being found to be not only stable in presence of sea-water but to possess excellent mechanical properties.

Deval's researches * on the effect of direct addition of calcium sulphate to various cements confirm the above theory. Each of the finely ground cements tested was completely hydrated by mixing with 50 per cent of water and storing the mixture under water for three months out of contact with carbon dioxide. The mass was then dried, reground,

* Abstract in Jour. Soc. Chem. Industry, vol. 21, pp. 971–972.

mixed with half its weight of calcium sulphate and 33 per cent of water, and made up into rods which were kept moist and protected from carbon dioxide by storage on moistened filter-paper under a glass bell. At the end of three weeks the increase in length of the rods was measured with the following results:

TABLE 167.

EFFECT OF ALUMINA.

Type of Cement.	Per Cent of Alumina in Cement.	Per Cent of Elongation of the Rods.
Slag cement (Vitry)	15.5	27
" " (Champignolles)	14.5	16
Grappier cement (Besses)	7.5	14
Portland cement	6.2	12
Hydraulic lime (Besses)	4.7	4

It will be noted that the percentage of elongation of the rods varied directly with the percentage of alumina in the cements tested, proving conclusively that the swelling was due to the action of the calcium sulpaluminate formed during the operation.

Iron oxide.—Iron oxide, though usually so low as to be negligible in a Portland cement, occasionally is present in considerable percentages (4 to 6 per cent). When this is the case, it can only be considered as equivalent to alumina in its action, allowing, of course, for their difference in combining weights. This conclusion is borne out by the fact that Portland cements practically free from alumina have been made, containing lime, silica, and iron oxide only.

Sulphur.—Sulphur, when present in a cement mixture, may occur either as a sulphide or sulphate. In the former condition it is usually due to the occurrence of pyrite (iron disulphide, FeS_2) either in the limestone, or in the clay. When present as a sulphate, it is usually in the form of gypsum (hydrous calcium sulphate, CaS_4+2H_2O).

In the rotary kiln, which usually has an abundantly oxidizing flame, it is probable that any calcium sulphate present is dissociated ($CaSO_4 = CaO+SO_3$) and the sulphur trioxide carried off, as this dissociation occurs at a temperature much lower than that reached in clinkering. If the flame is not sufficiently oxidizing, however, and because of imperfect draft this condition is likely to occur in vertical kilns, any lime sulphate present will be reduced to the sulphide form.

Alkalies.—Small percentages of soda and potash are usually present in the mixture, due mostly to their presence in the clay or shale. Alka-

lies have been regarded as detrimental, as inert, and as beneficial; and much discussion has taken place on the subject, based mostly on purely theoretical considerations.

In experimenting with various methods for analyzing Portland cement, Hillebrand encountered the question of loss of alkalies during burning, which he discusses * as follows:

" Long before the last of the sulphur trioxide is expelled alkali begins to volatilize, and it is easy to remove all or nearly all in this manner. The alkali is volatilized as oxide and may be collected in quantity on the under side of the crucible lid. At the intense temperature of the rotary-kiln furnace this action must play an important part, and to it is to be attributed the great loss of alkali noted by me in the cement of 1901, as compared with the raw mix from which it was made, an observation which is repeated in the present case and must be general in cement-burning."

Phosphorus.—Phosphorus, combined with lime in the form of lime phosphate, frequently occurs in notable percentages in limestones, particularly in the soft, chalky limestones and " marls " of the Southern States. In analyses this will be reported as phosphoric acid or phosphorus pentoxide (P_2O_5), when it is determined at all. Few commercial analysts, however, would look for it in a cement material and it is therefore rarely reported.

Late in 1903 samples of a " marl " and clay from a Southern State were sent to a leading testing laboratory to obtain a decision on their value as cement materials. Three different burnings of cement were made from the raw materials in various mixtures, and the resulting cements gave the test shown in Table 169, below. In addition to these generally poor results the chemists reported that the cement, for a week or so after setting, was so soft that it could be readily rubbed off by the hand. The various defects in the cements were ascribed by the laboratory experts to the presence in the marls of notable percentages of phosphoric acid. The matter was referred to me by the Southern company, and at my request Prof. Clifford Richardson examined microscopically several thin sections of the clinker which had been made in the laboratory tests. He reported that the raw mix had been very coarsely ground and the clinker underburned.

The raw materials, as analyzed at the laboratory, showed the results given in Table 168. Two samples of marl were tested and one of clay.

Of the three samples of cement made up from these materials and tested as below (Table 169), Cements A and B were made by mixing

* Journ. Amer. Chem. Soc., vol. 25, p. 1200. 1903.

Marl 1 and clay in different proportions, while Cement C was made from a mixture of Marl 2 and the same clay.

TABLE 168.

ANALYSES OF RAW MATERIALS CONTAINING PHOSPHORIC ACID.

	Marl 1.	Marl 2.	Clay.
Silica (SiO_2)	9.02	9.99	38.96
Alumina (Al_2O_3)	3.88*	2.05	22.60
Iron oxide (Fe_2O_3)	1.10	1.20	5.82
Lime (CaO)	45.78	45.82	16.44
Magnesia (MgO)	0.75	0.80	0.32
Volatile (CO_2, etc.)	38.87	37.99	16.02
Phosphorus pentoxide (P_2O_5)	.....	1.23	

* Including about 1 per cent P_2O_5.

TABLE 169.

TESTS OF CEMENTS CONTAINING PHOSPHORIC ACID

		Cement A.	Cement B.	Cement C.
Composition:	Silica (SiO_2)	22.20	21.87	24.26
	Alumina (Al_2O_3)	10.23†	6.84	7.97
	Iron oxide (Fe_2O_3)	2.64	2.60	3.22
	Lime (CaO)	63.83	64.85	58.74
	Magnesia (MgO)	1.11	1.30	1.21
	Phosphorus pentoxide (P_2O_5)	See Al_2O_3	2.50	3.82
Per cent plaster added		1½%	2%	1½%
Fineness:	Passing 50-mesh sieve	100.0	100.0	100.0
	" 100- " "	96.3	98.8	94.0
	" 200- " "	76.0	80.0	71.0
Setting time:	initial	1 hr. 10 min.	1 hr. 25 min.	12 min.
	final	5 hrs. 0 min.	7 hrs. 10 min.	18 min.
Tensile strength:	neat, 1 day	56 lbs.	49 lbs.	173 lbs.
	" 7 days	510 "	531 "	213 "
	" 28 "	754 "	754 "	340 "
	1:3, 7 "	180 "	166 "	72 "
	" 28 "	327 "	280 "	80 "

† Including about 2 per cent P_2O_5.

Influence of intentionally added fluxes.—At a number of plants working on materials or mixtures which are naturally difficult to fuse, experiments have been made on the reduction of the clinkering temperature by the addition of fluxing materials. Experiments of this

kind are usually taken up in the early stages of the manufacturer's experience. They rarely outlast the first year of actual practice, because he then begins to realize that it is difficult enough to secure a homogeneous and uniform mixture of two ingredients without going to the extra trouble of adding a third material. Occasionally, however, the fluxing mania persists, and in a few rare cases it may be entirely justifiable. Coal ash, for example, is often useful.

Fluorspar, sodium carbonate, and other alkali salts are the favorite materials for use as fluxes. It is certainly true that the addition of a very small percentage of some of these salts will decrease materially the difficulty of clinkering a cement mixture. Any other effect they may have on the cement, however, is either negatively or positively harmful; and in all cases their use can be avoided and equally good burning results obtained by a slightly increased fineness of grinding of the raw materials.

The direct addition of iron oxide as a flux, a practice which is followed by several American and French plants, is somewhat different from the use of fluorspar or alkalies. The iron oxide decreases the clinkering temperature very materially and gives a slower setting product than would an equal percentage of alumina. Adding it separately to the mixture is, however, a difficult matter to arrange. The more natural course to pursue would be to look for another source of clay supply, attempting to find a clay sufficiently high in iron to obviate the necessity for adding iron oxide separately.

Calculating Mixtures of Untried Materials.

When absolutely untried raw materials are being tested for the first time, the experimental mixture must be solely on the basis of their analyses, as developed in the formula given below or in some similar device. After the plant has once started, more empirical methods of calculating the mix are used, as set forth in a later section (pp. 368–370).

Cementation Index.—Recalling the discussion on page 359 of the theoretical constitution of Portland cement, it is evident that the ideal cement (and therefore the cement mixture) should contain its various ingredients in such percentages that all of the lime present can combine with all the silica, alumina and iron in practice. These conditions are satisfied if the formula below, called for convenience the Cementation Index, gives a value of *unity*. In this formula the chem-

ical equivalents above noted have been changed into percentages. The Index is empirical, but useful.

$$\frac{(2.8\times\text{percentage silica } (SiO_2))+(1.1\times\text{percentage alumina, } Al_2O_3)+(.7\times\text{percentage iron oxide, } Fe_2O_3)}{(\text{Percentage lime, CaO})+(1.4\times\text{percentage magnesia, MgO})}.$$

When the value given by this formula falls below 1.0 the cement must necessarily contain free lime or free magnesia; when it rises above 1.0, the cement must necessarily be lower in lime than is theoretically possible. The aim of the manufacturer, therefore, is to get a cement whose Cementation Index is on the safe side (i.e., over 1.0), but not too much so.

Use of the formula in proportioning mixtures.—The use of a similar formula in calculating mixtures to be made from untried materials has been well described by Prof. Newberry. The discussion here presented differs from his only in the fact that the magnesia and iron are allowed for, a correction which now seems necessary.

Following this rule, the various steps in the proportioning of a cement mixture are given below in sufficient detail to be readily followed.

OPERATION 1. Multiply the percentage of silica in the clayey material by 2.8, the percentage of alumina by 1.1, and the percentage of iron oxide by 0.7; add the products; subtract from the sum thus obtained the percentage of lime oxide in the clayey material plus 1.4 times the percentage of magnesia and call the result *n*.

OPERATION 2. Multiply the percentage of silica in the calcareous material by 2.8, the percentage of alumina by 1.1, and the percentage of iron oxide by 0.7; add the products and subtract the sum *from* the percentage of lime oxide plus 1.4 times the percentage of magnesia in the calcareous material, calling the result *m*.

OPERATION 3. Divide *n* by *m*. *The quotient will be the number of parts of calcareous material required for one part of clayey material.*

Example. Assuming that materials of the following composition are in use the operation would be as follows:

	Clay.	Limestone.
Silica (SiO_2)	62.2	2.4
Alumina (Al_2O_3)	16.1	2.0
Iron oxide (Fe_2O_3)	4.2	0.3
Lime (CaO)	1.6	50.2
Magnesia (MgO)	1.2	1.5
Sulphur trioxide (SO_3)	1.7	0.6
Alkalies (K_2O,Na_2O)	0.8	0.4
Water, carbon dioxide, etc	12.2	42.6

Operation (1). Clay.

Silica	$\times 2.8 = 62.2 \times 2.8 =$	174.16
Alumina	$\times 1.1 = 16.1 \times 1.1 =$	17.71
Iron oxide	$\times 0.7 = 4.2 \times 0.7 =$	2.94
		194.81

Lime	$\times 1.0 = 1.6 \times 1.0 =$	1.6
Magnesia	$\times 1.4 = 1.2 \times 1.4 =$	1.68
		3.28

$$194.81 - 3.28 = 191.53 = n.$$

Operation (2). Limestone.

Silica	$\times 2.8 = 2.4 \times 2.8 =$	6.72
Alumina	$\times 1.1 = 2.0 \times 1.1 =$	2.20
Iron oxide	$\times 0.7 = 0.3 \times 0.7 =$	0.21
		9.13

Lime	$\times 1.0 = 50.2 \times 1.0 =$	50.2
Magnesia	$\times 1.4 = 1.5 \times 1.4 =$	2.10
		52.30

$$52.30 - 9.13 = 43.17 = m.$$

Operation (3).

$\frac{n}{m} = \frac{181.53}{43.17} = 4.20 =$ parts of limestone to be used for each part of clay, by weight.

It must be recollected that the value given by the above formula represents the highest amount of lime theoretically possible under the best possible conditions of fine grinding and thorough burning. Even in the best-run plants these conditions cannot be attained in practice, and in a trial run either in a test kiln or in an actual plant it is foolish to attempt to reach this limit. The limestone shown by the formula should therefore be reduced in order to get safe results. A reduction of 10 per cent will probably be satisfactory. In the example given above this would work out as follows:

4.2 = parts limestone (to 1 of clay) allowed by formula
0.42 = 10 per cent reduction for safety

3.78 = parts limestone (to 1 of clay) to be actually used.

Calculating Mixtures in Current Work.

After a plant has once gotten into good working order, and as long as the same raw materials are in use, the calculation of the mix becomes a much simpler affair. Two general methods are in use:

At most plants the percentage of carbonates in the mix is made the criterion. If good results have been attained with mixtures carrying 78 to 80 per cent total carbonates ($CaCO_3+MgCO_3$), the aim of the chemist is simply to keep the mix within these limits. The calculation in this case is simply a matter of arithmetic which does not require explanation. The other method is to keep a fixed ratio between the total insoluble matter and the total carbonates. This ratio will naturally be different at each plant, but will always be fairly constant at any one plant.

In a well-known and admirably managed marl-plant the marl is analyzed after being pumped into tanks at the mills, and the clay on its arrival at the mill. Four determinations are made on each sample of marl and three on the clay. These are:

Marl. 1. Percentage of water;
2. Weight per cubic foot;
3. Percentage of insoluble matter;
4. Percentage of carbonates.

Clay. 1. Percentage of water;
2. Percentage of insoluble matter;
3. Percentage of carbonates.

From these determinations the mix is proportioned in such a way that the ratio

$$\frac{\text{Carbonates}}{\text{Insoluble matter}}$$

shall fall within certain numerical limits. At the plant in question, which runs a high-testing cement which is also very high in silica, the above formula is made to give a value of 4.2. In the majority of plants it would fall about 3.0 to 3.4.

Composition of mixture.—The cement mixture ready for burning will commonly contain from 74 to 77.5 per cent of lime carbonate, or an equivalent proportion of lime oxide. Several analyses of actual cement mixtures are given in the following table. The ratio of silica to alumina plus iron for ordinary purposes should be about 3:1, for the

cement becomes quicker setting and lower in ultimate strength as the percentage of alumina increases. If the alumina percentage be carried too high, moreover, the mixture will give a fusible, sticky clinker when burned, causing trouble in the kilns.

TABLE 170.

COMPOSITION OF ACTUAL MIXES.

Silica (SiO_2)	14.77	12.85	15.18	11.8	13.52
Alumina (Al_2O_3)	4.35	4.92	6.42	8.2	6.56
Iron oxide (Fe_2O_3)		1.21			
Lime (CaO)	43.03	42.76	42.97	41.8	42.07
Magnesia (MgO)	1.74	1.02	n. d.	0.8	2.07
Carbon dioxide (CO_2)	35.61	34.71	n. d.	n. d.	35.31
Water	n. d.	n. d.	n. d.	n. d.	n. d.
Silica (SiO_2)	13.46	13.85	12.62	14.94	12.92
Alumina (Al_2O_3)	n. d.	7.20	6.00	2.66	4.83
Iron oxide (Fe_2O_3)	n. d.			1.10	1.77
Lime (CaO)	41.25	41.40	42.26	42.34	42.30
Magnesia (MgO)	n. d.	n. d.	2.67	2.21	2.08
Carbon dioxide (CO_2)	34.86	36.42	36.10	35.68	35.49
Water			n. d.	n. d.	n. d.

Methods of control.—The chemist having determined the standard of composition which he wishes to maintain in the mix, several different methods of maintaining this standard are possible. Theoretically, of course, the best of these methods is:

(1) Both raw materials are analyzed as they arrive at the mill; the mix is made according to these analyses; after grinding the mix is analyzed as a check, and if seriously incorrect is corrected by the addition of the necessary ingredients. This method is actually practiced at some plants, but in general one or the other of its two elements is gradually dropped out, so that most plants approach one of the two following extremes in practice.

(2) The raw materials are analyzed, either by borings in the quarry or by an arrival at the mill, and the mix made in accordance with these analyses. The mix may be analyzed occasionally as a check, but no serious attempt is made to correct it. In this method the entire reliance is placed on the analyses of the raw materials. With hard, dry, raw materials varying little in composition the plan works well. In dealing with marls, etc., the third plan is most used.

(3) The raw materials are mixed without analysis in approximately correct proportions, according to previous experience, and the ground

mix is analyzed and brought up to proper composition (standardized) by the addition of whichever raw material proves to be deficient. In this method the correction of the mix is a regular part of the procedure. For convenience the mix is usually made always a little low in the same constituent, so that only one tank or bin of raw material needs to be kept on hand for standardizing.

It is this possibility of correcting a mix in advance of burning, and without interrupting the normal operation of the mill that gives the wet process its most important advantage. Comparison of long series of results at a very large number of mills, both American and foreign, leaves little doubt on this one point; that the wet process mills do in current practice run more evenly from day to day, so far as the regularity in composition of their mix and cement are concerned.

Changes in Composition During Manufacture.

In theory the cement produced should correspond in composition to the mixture from which it is made. In practice it is found that in addition to the expected loss of water, carbon dioxide, and other volatile components, the cement has suffered other changes which prevent it from having the exact composition calculated from the mixture. During the process of burning, the clinker has taken up a certain amount of material from the fuel ashes, the kiln linings, or the gases produced in the kiln. The changes in composition thus caused will be briefly discussed.

The change in composition during burning is almost inevitably in the direction of raising the Cementation Index of the cement, i.e., making it more clayey. This is due to the fact that the impurities picked up during burning are all of a clayey character, the kiln linings and the fuel ash being predominantly composed of silica and alumina. To partly counterbalance these additions of clayey matter, it is probable that the dust blown out of the kiln is more clayey than the rest of the mix; but this is not sufficient in amount to avail much against the combined influence of the fuel ash and the kiln lining. Of the two factors the fuel ash is by far the most important, because the kiln bricks are pretty steadily covered by a skin of clinker.

The variation in composition of the ash derived from certain types of fuel is shown by the following analyses made by Candlot,* but more typical analyses of normal coal ash are on page 455.

* Bonnami. Fabrication et Controle des Chaux Hydrauliques et des Ciments, p. 58.

TABLE 171.

ANALYSES OF FUEL ASH.

	Composition of Ash from	
	Anthracite.	Gas Coke.
SiO_2	40.10	29.30
Al_2O_3	42.80	19.63
Fe_2O_3	4.70	14.64
CaO	8.10	10.64
MgO	0.90	2.70
SO_3	1.23	13.72

The differences between the calculated and actual compositions of a cement are well illustrated by the example given below. In this case a marl and clay of determined composition were mixed in a known ratio. The composition which a cement made from this mixture *should* show was calculated and is given in column 3, while the composition of the cement actually resulting is given in column 4. For these data the writer is indebted to Prof. S. B. Newberry, who carried out the test in question.

TABLE 172.

CHANGE IN COMPOSITION DURING BURNING.

	Raw Materials.		Finished Product	
	Marl.	Clay.	Calculated.	Actual.
Silica (SiO_2)	1.16	57.08	22.20	22.42
Alumina (Al_2O_3)	0.75	10.01	5.02	5.68
Iron oxide (Fe_2O_3)	0.75	5.37	2.85	3.22
Lime (CaO)	49.44	8.32	65.79	62.24
Magnesia (MgO)	2.04	5.22	4.06	3.22
Loss (H_2O,CO_2, etc.)	46.40	14.00	n. d.	n. d.
Cementation Index	.....	.....	0.974	1.068

This point is also illustrated by the following analyses of raw mix and cement from the Syracuse plant, analyzed by Hillebrand.*

* Jour. Amer. Chem. Soc., vol. 25, p. 1186. 1903.

TABLE 173.

CEMENT MIXTURE AND CEMENT, SANDUSKY.

	Mix.	Cement.
Silica (SiO_2)	13.51	21.93
Alumina (Al_2O_3)	3.32	5.68
Titanic oxide (TiO_2)	0.18	0.31
Iron oxide (Fe_2O_3)	1.43	2.35
Lime (CaO)	40.84	62.92
Magnesia (MgO)	0.75	1.10
Potash (K_2O)	0.79	0.61
Soda (Na_2O)	0.22	0.29
Sulphur (S)	0.16	0.09
Sulphur trioxide (SO_3)	1.43	1.53
Carbon dioxide (CO_2)	n. d.	1.73
Water	4.20	1.40
Cementation Index	1.014	1.075

It will be seen that in both these experiments the Cementation Index of the cement has been raised considerably by the amount of silica and alumina taken up during calcination.

CHAPTER XXVIII.

PREPARING THE MIXTURE FOR THE KILN.

THE preparation of the raw materials for burning involves the reduction of both ingredients to a very fine powder and their intimate mixture in proper proportions. In practice the two operations—grinding and mixing—are usually carried on to some extent simultaneously; the raw materials are commonly crushed and ground more or less finely and then well mixed, during and after which mixing the final reduction to powder takes place.

Two general methods of preparation for the kiln are in use at different plants—the dry and the wet, the dry method being almost invariably followed unless the limey constituent of the mixture is a marl already full of water. This dry method consists merely in keeping the materials in as dry a condition as possible throughout the entire process of grinding and mixing, any small percentage of moisture they may naturally contain being removed by driers early in the process. In the wet method, on the other hand, the materials are powdered and mixed while in a very fluid state, containing usually 35 per cent or so of water.

In addition to these two main methods noted, it will be necessary to describe separately and briefly certain peculiar modifications of the dry method. Some of these modifications are practiced when slag is used as one of the raw materials, certain changes in the process being introduced which are of both technologic and commercial interest. The other modification of the dry process is an interesting type in which the materials are actually fused in a furnace. This requires description because of the eminence of the engineers who have devised it, and because of its possible future importance.

Certain features in regard to crushing and grinding are common to all methods of preparing the mix, and these general principles and features together with notes on power employed in plants and on crushing machinery in general will be described in Chapter XXIX.

In the present chapter the various methods of preparation will be taken up in the following order.

(1) Normal dry methods;
(2) Methods with slag-limestone mixtures;
(3) Blast-furnace methods;
(4) Wet methods.

(1) Dry Methods of Preparation.

In dry methods of preparation the raw materials are almost always dried to remove any natural moisture they may contain. This drying may take place entirely before the grinding has commenced; or, as is more usual, the two raw materials are first crushed and partly reduced separately, then dried, and finally mixed and pulverized. For convenience, however, the subject of drying will be taken up first.

Drying the raw materials.—With the exception of the marls and clays used in the wet method of manufacture, Portland-cement materials are usually dried before the grinding is commenced. This is necessary because the raw materials as they come from the quarry, pit, or mine will almost invariably carry appreciable, though often very small, percentages of water, which greatly reduces the efficiency of most modern type of grinding-mills and tends to clog the discharge screens.

Percentage of water in raw materials.—The percentage of water thus carried by the crude raw material will depend largely on the character of the material, partly on the method of handling and storing it, and partly on weather conditions.

In the case of hard limestones freshly quarried, the water will commonly range from ½ per cent to 3 per cent, rarely reaching or exceeding the higher figure except in the very wet quarries or during a rainy season. Such limestones, comparatively dry when quarried, are frequently sent to the grinding-mills without artificial drying.

With the soft, chalky limestones, which absorb water very rapidly, the percentage can usually be kept down to 5 per cent or less in dry weather, while prolonged wet weather may necessitate the handling at the mill of material carrying as high as 15 to 20 per cent of water.

The clays present a much more complicated case. In addition to the hygroscopic or mechanically held water that they may contain, there is also always present a certain percentage of chemically combined water. The amount of hydroscopic water present will depend on the treatment and exposure of the clay, and may vary from 1 per cent or so in clays which have been stored and air-dried to as high as 30 per cent in fresh clays. The chemically combined water will depend

largely on the composition of the clay, and may vary from 5 to 12 per cent. The hydroscopic or mechanically held water of clays can be driven off at a temperature of 212° F., while the chemically combined water is lost only at a low red heat. The total water, therefore, to be driven off from clays may range from 6 to 42 per cent, depending on the weather, the drainage of the clay-pit, and the care taken in preventing unnecessary exposure to moisture of the excavated clay. The average total amount of moisture will probably be about 15 per cent.

In dealing with shales, the mechanically held water will rarely rise about 10 per cent, and can commonly be kept well below that limit. An additional 2 to 7 per cent of water will be carried by any shale in a state of chemical combination.

At a few plants marl is used with clay in a dry process. As noted elsewhere the marls as excavated carry usually about 50 per cent of water. Marl presents a more difficult problem than do the other raw materials, because the vegetable matter usually present in marls is extremely retentive of water.

It will be seen, therefore, that cement materials may carry from 1 per cent to 50 per cent of water when they reach the mill. The average throughout the country would probably fall close to 5 per cent if the marls are excluded. In a dry process it is necessary to remove practically all of this water before commencing the grinding of the materials. One reason for this is that fine pulverizing cannot be economically or satisfactorily accomplished unless absolutely dry material is fed to the grinding machinery. Another reason, which is one of convenience rather than of necessity, is that the presence of water in the raw materials complicates the control of the cement mixture.

Methods and costs of drying.—The type of dryer used at most cement-plants is a cylinder approximately 5 feet in diameter and 40 feet or so in length, set at a slight inclination to the horizontal and rotating on bearings. The wet raw material is fed in at the upper end of the cylinder, and it moves gradually toward the lower end, under the influence of gravity, as the cylinder revolves. In many dryers angle irons are bolted to the interior in such a way as to lift and drop the raw material alternately, thus exposing it more completely to the action of the heated gases and materially assisting in the drying process. The dried raw material falls from the lower end of the cylinder into an elevator boot and is then carried to the grinding-mills.

The drying-cylinder is heated either by a separate furnace or by waste gases from the cement-kilns. In either case the products of combustion are introduced into the cylinder at its lower end, are drawn

through it, and escape up a stack set at the upper end of the dryer.

The dryer above described is the simplest and is most commonly used. For handling the small percentages of water contained in most cement materials it is very efficient, but for dealing with high percentages of water, such as are encountered when marl is to be used in a dry process, it seems probable that double-heating dryers will be found more economical.

This type is exemplified by the Ruggles-Coles dryer, a detailed description of which is given in the section on slag cements, page 593. In this dryer a double cylinder is employed. The wet raw material is fed into the space between the inner and outer cylinders, while the heated gases pass first through the inner cylinder and then, in a reverse direction, through the space between the inner and outer cylinders. This double-heating type of dryer is employed in almost all of the slag-cement plants in the United States, and is also in use in several Portland-cement plants.

When vertical kilns were in use, drying-floors and drying-tunnels were extensively used, but at present they can be found only in a few plants, being everywhere else supplanted by the rotary dryers.

At a marl-plant of the ill-fated Hecla Portland Cement Company, which is shown in Fig. 82, rotary kilns were actually used as driers, because of the extreme difficulty encountered in properly drying this material in a drier of ordinary type.

In the Edison plant a stationary vertical tower drier is used for the cement rock and limestone.

The Edison stack drier shown in Fig. 83 is described as follows in a recent article * in the *Iron Age:* The chimney surmounting this flue is used only when starting a fire, the gases of combustion ordinarily passing directly to the dryer stack to rise through the falling stream of rock and thoroughly dry it. The baffle-plate system is such that the fall of a piece of rock from the lowest screen to the bottom of the dryer requires 26 seconds. From above the baffles near the top of the stack the gases are drawn out by an 80-inch exhaust-fan, driven by a 50-horse-power motor, and are passed through a dust-settling chamber on their way to the atmosphere. A 12-inch screw conveyor returns the collected dust to the bottom of the dryer stack and replaces it in the system. The baffle-plates of the upper sections of the stack are arranged to slide longitudinally in their slots, reciprocating motion being provided by a motor-driven system of rocker arms sliding

* The Iron Age, Dec. 24, 1903, p. 5.

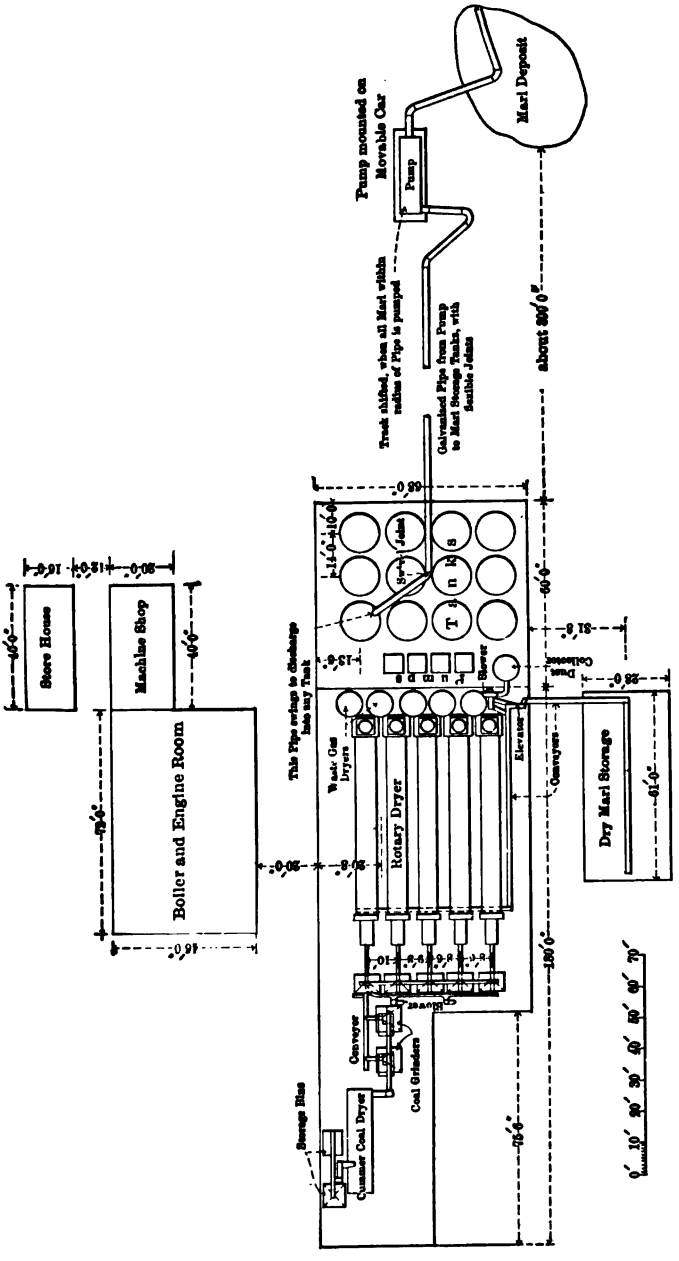


FIG. 82.—Marl-drying plant, Hecla P. C. Co. (Engineering News.)

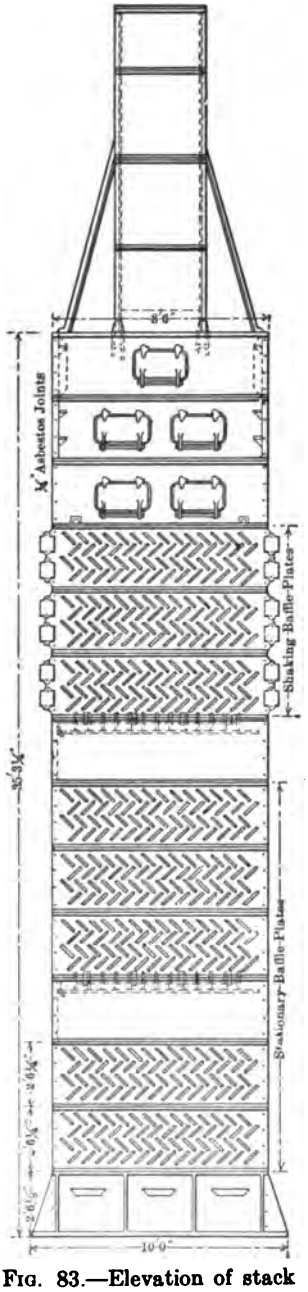


FIG. 83.—Elevation of stack drier, Edison plant. (Engineering News.)

successive rows of plates in opposite directions at the rate of 20 cycles per minute. By this action clogging of possibly damp rock is prevented until it has fallen far enough to be dried sufficiently to have no such tendency. The shear-pin principle, used at this plant for driving the crushing rolls, is also applied in a modified form to the baffle-shakers. The rock-dryer is 8×8 feet in plan section, 40 feet high, and has a capacity of 3000 tons per day, the same as the crusher plant. The performance of the dryer stack is very efficient; the fuel consumption is small, the percentage of moisture in the crushed rock is reduced from 3 or 4 per cent to within 1 per cent, and the gases leave at a temperature scarcely above 212°. A blower equipment is provided for increasing the furnace draft when necessary.

The cost of drying raw materials will depend on the cost of fuels, the percentage of water present in the wet material, and the efficiency of the dryer. Dryers are usually arranged and located so as to require little attention, and the labor costs of drying are therefore slight. Even under the most unfavorable conditions 5 lbs. of water can be expected to be evaporated for each pound of coal used, while a good dryer will usually evaporate 7 or 8 lbs. of water per pound of coal. Marls containing much organic matter are notably more retentive of moisture than any other raw material, and a marl-drying proposition is therefore apt to be expensive. For a full description of a most elaborate and unsuccessful installation for marl-drying, reference should be made to the paper cited below.*

* Plant and buildings of the Hecla Portland Cement and Coal Co. Engineering News, vol. 51, pp. 243–245. 1904.

General methods.—Usually the limestone or cement rock is passed through a crusher at the quarry or mill before being sent to the dryer; and occasionally one or both of the raw materials is still further reduced before grinding, but the principal part of the grinding process always takes place after the material has been dried.

After drying, the two raw materials may either be mixed immediately or each may be separately reduced before mixing. Automatic mixers, of which many slightly different types are in use, give a mixture in the proportions determined upon by the chemist.

The further reduction of the mixture is usually carried on in two stages, the material being ground to from 20 to 40 mesh or even finer in a ball mill or a high-speed mill (Griffin, Fuller-Lehigh, Maxecon, Huntingdon, etc.); and finished in a tube-mill. At a few plants, however, single-stage reduction is still practiced with more or less success.

As between the different combinations of grinding and pulverizing machinery that are in actual use, there is relatively little choice as to costs of operation, power consumed, etc. This is indicated clearly enough, if there were any doubt, by the diverse practices of the largest companies. The matter is further referred to in the following chapter.

Plans of actual plants.—Plans of several actual plants have been inserted for the purpose of illustrating the brief statement made above.

The plant of the Lawrence Cement Company, of Siegfried, Pa., published by courtesy of Messrs. Lathbury and Spackman, is given in Fig. 84. The materials used here are cement rock and limestone. These are separately crushed in Gates crushers and dried in rotary driers, after which they are mixed and reduced in Williams mills and tube mills.

The plant of the Hudson P. C. Co., a typical modern dry-process plant, is shown in Fig. 85, reproduced by courtesy of *Engineering News*. In the article * accompanying this figure, the raw side of the mill is described as follows:

"Following the course of the material step by step, it will be seen that the loaded cars from the quarry come into the mill at the east end at an elevation of 12 feet above the crusher-room floor, which is itself elevated 13½ feet above the main mill floor, and that they dump through the track onto the crusher-room floor. Flush with this floor are the tops of three rotary crushers, two for crushing limestone and one for crushing shale. The two limestone crushers are run by a 45-H.P. electric motor and the shale crusher by a 22-H.P. electric motor. From the crushers the stone is delivered, shale and limestone separately, into

* Engineering News, vol. 50, pp. 70, 71. July 23, 1903.

four rotary driers, each of which is operated by a 5-H.P. electric motor. From the driers the stone passes separately to the ball mills for the first grinding. These ball mills are of the Krupp type, and there are five of them, each operated by a 50-H.P. electric motor. From the ball mills the shale powder is delivered to a set of two bins and the limestone powder to a set of five bins. These bins are so constructed as to discharge automatically into a double elevator, whence the materials

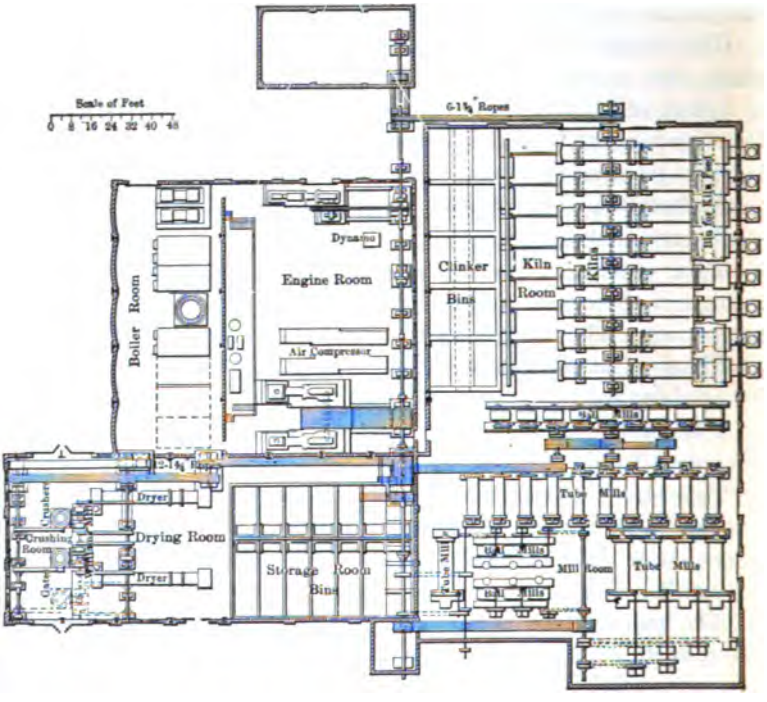


FIG. 84.—Plan of plant, Lawrence Cement Co., Siegfried, Pa.

are discharged into a double hopper over a tandem automatic weighing-machine, which weighs out the proper proportion of each material. The two products are then mixed thoroughly by being conveyed together by elevator *E* and conveyors 9½ and 9 to the steel bins feeding the tube mills. There are six of these tube mills and they are driven in groups by a 75-H.P. electric motor.

"The tube-mill discharges feed onto a screw conveyor 10, thence to the elevator *EE*, and thence to screw conveyor 11, which discharges into two groups of stock bins. Screw conveyors 13 running under-

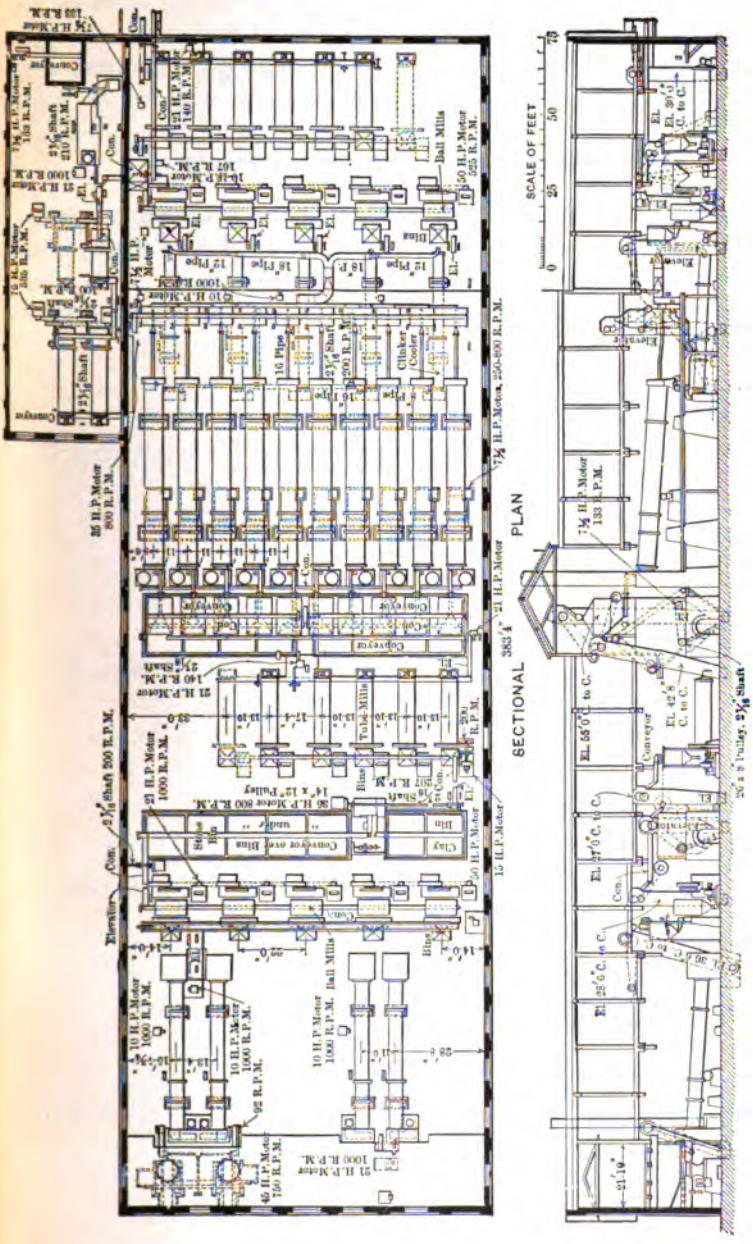


FIG. 85.—Plan of plant, Hudson P. C. Co., Hudson, N. Y. (Engineering News.)

neath these bins take the material right and left to the elevator *F*, which feeds the right and left screw conveyors 12 that discharge into the kiln feed bins. There are ten of these bins and each one feeds one rotary kiln."

Actual Equipments of Dry-process Plants.

The present-day practice in dry-process plants is shown better by the following data on the actual equipments of a number of these plants than by any amount of general statements on the subject. Reference should also be made to Chapter XXIX, where general crushing practice is discussed.

Plant No. 1. Uses limestone and shale.

Limestone	Shale
1 Gates crusher	1 Gates crusher
1 Mosser drier	
1 kominuter	
4 tube mills	
4 kilns	

Plant No. 2. Limestone and shale.

Limestone	Shale
1 crusher	
1 rotary drier	
1 Williams mill	
2 tube mills	
2 kilns	

Plant No. 3. Limestone and shale.

Limestone	Shale
1 crusher	1 tunnel drier
1 rotary drier	1 crusher
1 dry-pan to 30 mesh	
2 Raymond pulverizers	
3 kilns, 50 feet	

Plant No. 4. Limestone and shale.

Limestone	Shale
2 Alton crushers	1 dry-pan to 8-mesh
1 Bonnot drier	1 rotary drier
10 sets rolls	2 tube mills
9 sets Sturtevant emery mills	
4 intermittent tube mills	
4 kilns	

Plant No. 5. Uses fairly hard limestone, with shale.

Limestone	Shale
1 Gates crusher, coarse rock sold; screenings used in cement plant	1 disintegrator
2 Bonnot rotary driers	2 Bonnot rotary driers

3 kominuters to 20-mesh
4 tube mills to 92% through 100-mesh
8 kilns

Plant No. 6. Limestone and shale.

Limestone	Shale
1 Gates crusher	1 Gates crusher

1 rotary drier
3 ball mills
4 tube mills
6 kilns

Plant No. 7. Uses hard limestone and shale.

Limestone	Shale
2 Austin crushers	1 Sturtevant crusher
2 Bonnot driers	2 Bonnot driers
2 Krupp ball mills	1 Bonnot ball mill

5 tube mills
10 kilns

Plant No. 8. Limestone and shale.

Limestone	Shale

1 Gates crusher, No. 5
1 rotary drier
3 Williams mills
3 tube mills
6 kilns

Plant No. 9. Limestone and shale.

Limestone	Shale

2 crushers
2 rotary driers
4 ball mills
6 tube mills
8 kilns

Plant No. 10. Limestone and cement rock.

Limestone	Cement rock

2 crushers
2 rotary driers
6 ball mills
6 tube mills
10 kilns

Plant No. 11. Limestone and shale.

Limestone	Shale
1 crusher	1 disintegrator
1 rotary drier	1 rotary drier

2 kominuters
2 Davidsen tube mills
6 kilns, 60 feet

Plant No. 12. Uses marl and clay in a dry process.

Marl	Clay
1 rotary drier	1 rotary drier

2 tube mills
3 kilns

Plant No. 13. Limestone and shale.

Limestone	Shale
1 large gyratory crusher	1 gyratory crusher
2 smaller gyratories	Rotary drier
Rotary drier	1 Krupp ball mill
2 Krupp ball mills	

10 Fuller-Lehigh mills
5 kilns, 120 feet

Plant No. 14. Limestone and shale.

Limestone	Shale
1 large gyratory crusher	1 gyratory crusher
2 smaller gyratories	1 rotary drier
1 rotary drier	

3 Fuller-Lehigh mills
2 kilns, 160 foot

Plant No. 15. Limestone and shale.

Limestone	Shale
1 large gyratory crusher	1 rotary drier
1 smaller gyratories	
1 rotary drier	

Jeffrey hammer mills
Griffin mills
2 kilns, 140-foot

Plant No. 16. Limestone and slag.

Limestone	Slag
3 Gates gyratory crushers	4 rotary driers
Rotary driers	
8 Gates ball mills	3 Gates ball mills

12 tube mills
12 kilns, 120-foot

Plant No. 17. Limestone and shale.

Limestone	Shale
1 gyratory crusher	2 rotary driers
2 smaller gyratories	
2 rotary driers	
9 ball mills	2 ball mills
14 Gates tube mills	
24 kilns, 125-foot	

(2) Methods Used with Slag-Limestone Mixtures.

While the manufacture of Portland cement from a mixture of slag and limestone is similar in general theory and practice to its manufacture from a limestone-clay or other dry raw materials, certain interesting differences occur in the preparation of the mixture. In the following paragraphs the general methods of preparing mixtures of slag and limestone for use in Portland-cement manufacture will first be noted, after which certain processes peculiar to the use of this particular mixture will be described separately.

General methods.—After it had been determined that the puzzolan cement made * by mixing slag with lime without subsequent burning of the mixture was not an entirely satisfactory structural material, attention was soon directed toward the problem of making a true Portland cement from such slag. The blast-furnace slags commonly available, while carrying enough silica and alumina for a cement mixture, are too low in lime to be suitable for Portland cement. Additional lime must be added, usually in the form of limestone, the slag and limestone must be well mixed and the mixture properly burned. The general methods for accomplishing the proper mixture of the materials vary in details. It seems probable that the first method used in attempting to make a true Portland cement from slag was to dump the proper proportion of limestone, broken into small lumps, into molten slag. The idea was that both mixing and calcination could thus be accomplished in one stage; but in practice it was found that the resulting cement was variable in composition and always low in grade. This method has accordingly fallen into disuse, and at present three different general processes of preparing the mixture are practiced at different European and American plants.

1. The slag is granulated, dried, and ground, while the limestone is dried and ground separately. The two materials are then mixed

* See Part VII.

in proper proportions, the mixture is finely pulverized in tube mills, and the product is fed in a powdered state to rotary kilns.

2. The slag is granulated, dried, and mixed with slightly less than the calculated proper amount of limestone, which has been previously dried and powdered. To this mixture is added sufficient powdered slaked lime (say 2 to 6 per cent) to bring the mixture up to correct composition. The intimate mixture and final reduction are then accomplished in ball and tube mills. About 8 per cent of water is then added, and the slurry is made into bricks, which are dried and burned in a dome or chamber kiln.

3. Slag is granulated and mixed, while still wet, with crushed limestone in proper proportions. This mixture is run through a rotary calciner, heated by waste kiln gases, in which the temperature is sufficient not only to dry the mixture but also to partly powder it and to reduce most of the limestone to quicklime. The mixture is then pulverized and fed into rotary kilns.

Of the three general processes above described the second is unsuited to American conditions. The first and third are adapted to the use of the rotary kiln. The third seems to be the most economical, and has given remarkably low fuel consumption in practice, but so far has not been taken up in the United States.

Certain points of manufacture peculiar to the use of mixtures of slag and limestone will now be described.

Composition of the slag.—The slags available for use in Portland-cement manufacture are of quite common occurrence in iron-producing districts. Those best suited for such use are the more basic blast-furnace slags, and the higher such slags run in lime the more available they are for this use. The slags utilized will generally run from 30 to 40 per cent lime. The presence of over 3 per cent or so of magnesia in a slag is, of course, enough to render its use as a Portland-cement material inadvisable; and on this account slags from furnaces using dolomite (magnesian limestone) as a flux are unsuited for cement-manufacture. The presence of any notable percentage of sulphur is also a drawback, though, as will be later noted, part of the sulphur in the slag will be removed during the processes of manufacture.

Granulation of slag.—If slag be allowed to cool slowly, it solidifies into a dense, tough material, which is not readily reduced to the requisite fineness for a cement mixture. If it be cooled suddenly, however, as by bringing the stream of molten slag into contact with cold water, the slag is " granulated," i.e., it breaks up into small porous particles. This granulated slag or " slag sand " is much more readily pulverized

than a slowly cooled slag; its sudden cooling has also intensified the chemical activity of its constituents so as to give it hydraulic properties, while part of the sulphur contained in the original slag has been removed. The sole disadvantage of the process of granulating slag is that the product contains 20 to 40 per cent of water, which must be driven off before the granulated slag is sent to the grinding machinery.

In practice the granulation of the slag is effected by directing the stream of molten slag direct from the furnace into a sheet-iron trough. A small stream of water flows along this trough, the quantity and rate of flow of the water being regulated so as to give complete granulation of the slag without using an excessive amount of water. The trough may be so directed as to discharge the granulated slag into tanks or into box cars, which are usually perforated at intervals along the sides so as to allow part of the water to drain off.

Drying the slag.—As above noted, the granulated slag may carry from 20 to 40 per cent of water. This is renewed by treating the slag in rotary driers. In practice such driers give an evaporation of 8 to 10 lbs. of water per pound of coal. The practice of slag-drying is very fully described in Part VII of this volume, pages 592–595, where figures and descriptions of various driers are also given, with data on their evaporative efficiency. As noted earlier in this article, one of the methods of manufacturing Portland cement from slag puts off the drying of the slag until after it has been mixed with the limestone, and then accomplishes the drying by utilizing waste heat from the kilns. Kiln gases could, of course, be used anyway in the slag-driers, but it so happens that they have not been so used except in plants following the method in question.

Grinding the slag.—Slag can be crushed with considerable ease to about 50-mesh, but notwithstanding its apparent brittleness it is difficult to grind it finer. Until the introduction of the tube mill, in fact, it was almost impossible to reduce this material to the fineness necessary for a cement mixture, and the proper grinding of the slag is still an expensive part of the process, as compared with the grinding of limestone, shales, or clay.

Composition of the limestone.—As the slag carries all the silica and alumina necessary for the cement mixture, the limestone to be added to it should be simply a pure lime carbonate. The limestone used for flux at the furnace which supplies the slag will usually be found to be of suitable composition for use in making up the cement mixture.

Economics of using slag-limestone mixtures.—The manufacture of a true Portland cement from a mixture of slag and limestone presents

certain undoubted advantages over the use of any other raw materials, while it has also a few disadvantages.

Probably the most prominent of the advantages lies in the fact that the most important raw material—the slag—can usually be obtained more cheaply than an equal amount of natural raw material could be quarried or mined. The slag is a waste product, and a troublesome material to dispose of, for which reason it is obtained at small expense to the cement-plant. Another advantage is due to the occurrence of the lime in the slag as oxide, and not as carbonate. The heat necessary to drive off the carbon dioxide from an equivalent mass of limestone is therefore saved when slag forms part of the cement mixture, and very low consumption is obtained when slag-limestone mixture is burned.

Of the disadvantages, the toughness of the slag and the necessity for drying it before grinding are probably the most important. These serve to partly counterbalance the advantages noted above. A third difficulty, which is not always apparent at first, is that of securing a proper supply of suitable slag. Unless the cement-plant is closely connected in ownership with the furnaces from which its slag supply is to be obtained, this difficulty may become very serious. In a season when a good iron market exists the furnace manager will naturally give little thought to the question of supplying slag to an independent cement plant.

The advantages of the mixture, however, seem to outweigh its disadvantages, for the manufacture of Portland cement from slag is now a large and growing industry in both Europe and America. Four Portland-cement plants using slag and limestone as raw materials have been established for some time in this country, while a number are in operation in various European countries, notably in France and Germany.

References on slag-limestone mixtures.

(The more important articles are preceded by an asterisk.)

Eckel, E. C. Preparation of slag limestone mixtures. Municipal Engineering, vol. 25, pp. 227–230. 1903.

Hughes, O. J. D. Portland cement from slag. U. S. Consular Reports, No. 1700, July 18, 1903.

* Jantzen. Utilization of blast-furnace slag. Stahl und Eisen, vol. 23, pp. 361–375. 1902. Journ. Iron and Steel Inst., 1903, No. 1, pp. 634–637.

Kämmerer. Von Forell's process for the production of Portland cement from basic slag. Stahl und Eisen, vol. 19, p. 1088. 1899. Journ. Soc. Chem. Industry, vol. 19, p. 48.

*Lathbury, B. B., and Spackman, H. S. The Clinton Cement Company's plant, Pittsburg, Pa. The Rotary Kiln, pp. 82–85. 1902.

May, E. Slag (Portland) cement. Stahl und Eisen, vol. 18, pp. 205–211. 1897. Journ. Iron and Steel Inst., 1808, No. 1, pp. 461–464.

Schiele, F. Manufacture of Portland cement from slag at Lollar, Germany. Proc. Inst. Civ. Engrs., vol. 145, pp. 119–120. 1901.

Steffens, C. Portland cement from slag in Germany. Stahl und Eisen, vol. 20, pp. 1170–1171. 1900. Journ. Iron and Steel Inst., 1901, No. 1, pp. 439–440.

Von Forell, C. Patent Portland cement from slag. Journ. Soc. Chem. Industry, vol. 19, p. 50. 1899.

*Von Schwarz, C. The utilization of blast-furnace slag. Journ. Iron and Steel Inst., 1900, No. 1, pp. 141–152. Engineering News, Sept. 27, 1900. Engineering Record, June 2, 1900.

*Von Schwarz, C. Portland cement manufactured from blast-furnace slag. Journ. Iron and Steel Inst., 1903, No. 1, pp. 203–230.

(3) Blast-furnace Methods of Making Cement.

Attempts have been made to manufacture Portland cement by mixing the raw materials without grinding and burning the mixture to a state of complete fusion in a kiln resembling a blast-furnace in design and action. The Hurry and Seaman patents covering a method of this type are described as follows:*

Raw materials containing carbonate of lime, silica, and alumina are mixed with carbonaceous fuel, the combustion of which is supported by a blast of air supplied through tuyeres, and a pressure about 10 to 20 lbs. above that of the atmosphere is maintained in the furnace, whereby the materials are melted, the molten cement being afterward drawn off, cooled, and pulverized. The carbon dioxide derived from the carbonate of lime is reduced to carbonic oxide by the incandescent fuel, and in this atmosphere any oxide of iron in the raw materials is said to be reduced to metallic iron, which sinks and can thus be separated from the molten cement, whereby a superior product is obtained. The carbonate of lime may be preliminary calcined and the carbon dioxide introduced together with air into the calcining furnace, where it is reduced and then again burned to carbon dioxide. The increased pressure is maintained either by arranging the height of the kiln so that the combustion gases formed in the lower part are prevented from escaping freely by the height of the mass of materials above or by a throttle-valve arranged in the outlet at the top of the kiln.

* Journal Soc. Chem. Industry, vol. 21, p. 1079. 1902.

In carrying out their experimental work Hurry and Seaman used cement mixtures of normal Portland composition. Their practical failure according to a personal statement by Mr. Seaman, was due to two causes, very different in origin and in seriousness. First, the iron oxide contained in the mix was reduced and appeared as particles of metallic iron in the fused product. Second, the fused product, when ground, was very slow-setting indeed.

Both of these difficulties can be overcome, and the intrinsic advantages of a blast-furnace process are so great that it seems likely to reach further development in future. At present cement is being made both in blast-furnaces and in electric furnaces in France, as is noted later in discussing the high-alumina Portlands (pages 517–519).

The blast-furnace dispenses with the necessity for drying, crushing and pulverizing the raw materials; and simplifies the conveying problem very greatly. In the next chapter will be found data relative to the importance of these various items in our present systems.

(4) Wet Methods of Preparation.

During all the early stages of the Portland cement industry wet methods of preparing the mix were in use everywhere; the two raw materials were mixed and ground wet, the resulting " slurry " was dried on floors or in tunnels; and fed, in bricks or otherwise, to fixed kilns of one type or another. All this meant a good deal of time and of hand labor.

When the rotary kiln came into use dry methods of preparation became possible, and concurrent improvements in grinding machinery aided in the very general adoption of dry processes of preparation. By 1903, there were only a few plants using limestone in a wet mix; the remaining wet process plants were using marl, and the results at most of them were not at all brilliant. The marl mixtures were made very wet at most of the mills, and the coal consumption was correspondingly large. This effect on costs and output was so great as to mask certain very real advantages of the wet process.

In the past decade or so, however, we have seen the reappearance of the wet process, both in Europe and in America, under more favorable conditions.

As the matter stands now, the respective advantages and limitations of the wet process may fairly be summed up as follows:

(1) The wet process, using modern grinding machinery, can prepare a mix of proper fineness at a substantially lower power-cost than can the dry process on the same materials.

(2) The wet process saves, in addition, the cost of drying the raw materials.

(3) The wet process permits actual correction of the mix *before* burning, owing to the use of slurry tanks.

(4) The wet process, on the other hand, shows a lower output per kiln and a higher fuel consumption per barrel than the dry process. These effects are very noticeable in short kilns—say of 60 to 100 foot length. They disappear gradually as the kilns lengthen; kilns 200 feet and longer have shown results fairly comparable to the best results of the dry process.

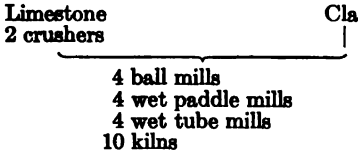
(5) To secure such economic results the percentage of water in the mix must be kept down rigidly to that just necessary to prevent settling in tanks or at other stages of the process. The old 50 to 60 per cent slurries were hopelessly uneconomical, even in long kilns. Experience at various mills with a wide variety of raw materials indicates that almost any slurry can be handled, if ground properly, with not over 35 per cent of water.

(6) The final cement of a wet process mill can be kept more uniform than in a dry mill. The wet process is therefore particularly applicable to localities whose raw materials are irregular in composition, and it is of maximum value under such conditions.

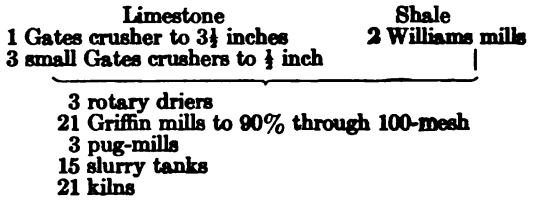
(7) In general the wet process, with very long kilns, is indicated for localities where the raw materials are either irregular in composition or are naturally wet, or difficult to dry (marls, chalks, some clays, etc.). Where the raw materials are naturally dry, or readily dryable; and at the same time regular in composition, the dry process is still the more economical of the two.

Actual Equipment of Wet-process Plants.

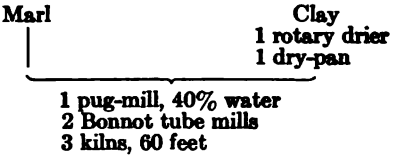
Plant No. 1. Uses a hard limestone and a clay in a wet process.



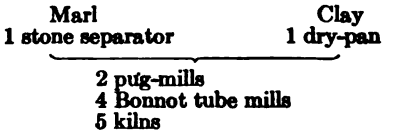
Plant No. 2. Uses a fairly hard limestone and a shale in a wet process.



Plant No. 3. Marl and clay.



Plant No. 4. Marl and clay.



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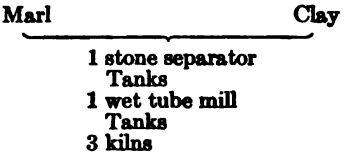
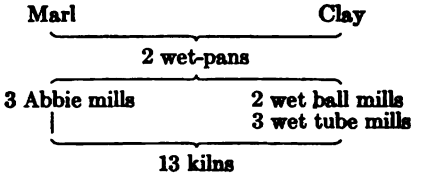
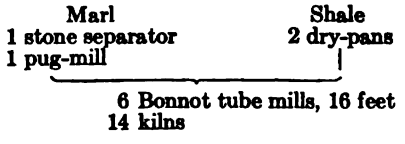


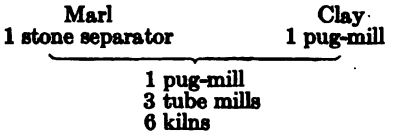
Plant No. 6. Marl and clay.



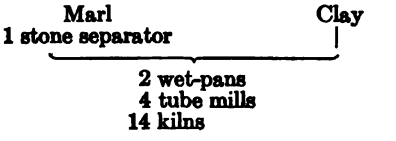
Plant No. 7. Marl and shale.



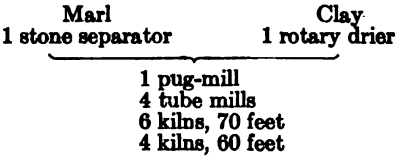
Plant No. 8. Marl and clay.



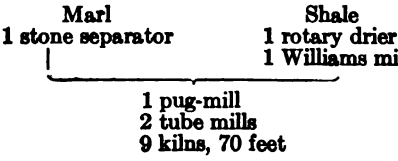
Plant No. 9. Marl and clay.



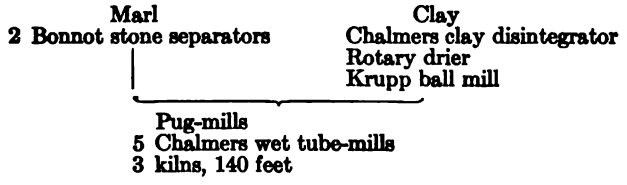
Plant No. 10. Marl and clay.



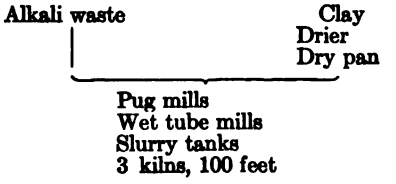
Plant No. 11. Marl and shale.



Plant No. 12. Marl and clay.



Plant No. 13. Alkali waste and clay.



Plant No. 14. Limestone and clay.

Limestone	Clay
Fairmount crusher	Wash-mill
Williams crusher	Tanks

Wet kominuters
3 tube mills
Slurry basins
2 kilns, 170 feet

Plant No. 15. Marl and clay.

Marl	Clay

Pug mills
Tanks
Tube mills
2 kilns, 100 feet

Plant No. 16. Limestone and clay.

Limestone	Clay
Gyratory crusher	Wash mills

3 wet kominuters
2 tube mills
Slurry basins
2 kilns, 235 feet

CHAPTER XXIX.

POWER AND GRINDING.

CERTAIN features of the power requirements and grinding practice at cement plants may conveniently be summarized in the present chapter, since they relate not only to the preparation of the raw material for the kiln, but to its later stages of burning and clinker-grinding. A statement of these general features will be of value, not only in giving an idea of present conditions, but as suggesting the probable lines along which further improvements will be most likely, because most profitable.

We may say, at the outset, that the average mill furnishes and employs a little less than 1 horse-power per daily barrel of cement produced; details on this point are stated below. This power is various in source, and in its means of transmission. But, whatever these may be, the power, always of about the same amount, is used in the mill chiefly for grinding the raw materials, and for grinding the clinker; and to a less important extent for operating the coal-grinding mill, the rotary kilns, the conveyors, the packing machinery, etc. With this preliminary outline in mind, attention can be turned to the sources, transmission, distribution and utilization of the power, in more detail.

Amount and source of power.—The amount of power supplied to and utilized by a cement mill has been decreasing slowly, on the average, for the past few decades, due in part to economies within the power system itself, and in part to improvements in the machinery which used the power. There are still mills using as much as 1¼ H.P. per daily barrel; there are others which make cement on ¾ H.P. per barrel or less; the average, for the total American output, is probably at present well below 1 H.P. per barrel.

In a few mills, particularly in the extreme west, where large hydro-electric plants supply extensive areas, the cement mills buy power entirely from such installations; in such cases both source and transmission are electric. But in by far the majority of cases the cement mill develops its own power by coal, and uses steam as a primary source. It may use this steam power direct, by shafts and belting; or it may convert it and transmit electrically to separate motors at the machinery.

One plant at least has a far more advanced layout—operating gas engines; but this is as yet unusual.

There are admittedly wide differences in economy, as regards both generation and transmission, but they are rather differences as between new and old mills than between the various power systems themselves. With the exception of the gas-engine—which as we see things now is over certain great areas of the world, if not everywhere, probably the power of the future—the choice is not very great in other ways. There are advantages about electric drive and separate motors; but in most mills these advantages do not amount to enough to affect the cost-sheet visibly. I should say that they are most noticeable in small and irregularly operated mills; and that for very large installations steam and shafting are still the most economical and satisfactory. In any case the choice is for each individual mill, because fuel and operating conditions are the decisive factors.

Distribution of power.—Assuming that the mill will use a little under 1 H.P. per daily barrel—say 20 H.P. hours per barrel for convenience, we may go on to consideration of its use and distribution among the processes. Here variations in processes and machinery will affect the results, but we can assume with sufficient accuracy that some 80 to 85 per cent of the total power will be used in the grinding of raw mix and clinker; the remainder will serve the other requirements of the average mill. As between the raw and clinker sides, the power used will be approximately equal; it will require, in other words, just about as much power to crush and pulverize 600 lbs. of raw material as to pulverize 380 lbs. of clinker. A wet-process mill will probably run its raw side on less; a dry process mill using hard limestone and shale may show lower proportionate use of power on its clinker side.

Taking current American practice to-day we will probably be not very far wrong if we assume that on the average the power used in the mill is close to

8 H.P. hours per daily barrel for preparing mix.
8 H.P. hours per daily barrel for finishing clinker.
4 H.P. hours per daily barrel for all other uses.

In studying possible economies in different lines we might further assume that the average H.P. hour will take 5 lbs. of coal. With coal at $2 per ton this is ½ cent per H.P. hour; with coal at $4 per ton it is just 1 cent per H.P. hour.

These facts suggest the limits within which we are necessarily confined in experimenting with such processes as the use of the blast fur-

nace, or pre-calcining the limestone; they also suggest forcibly, what is confirmed by examination of a long series of cost-sheets, that differences in type of grinding machinery are commonly of relatively small financial importance. Small improvements in kiln operations will save more coal than the worst possible grinding machinery can eat up; steadiness in quantity and quality of output will affect the cost sheet more than changes in mill practice.

Certain questions relating more directly to the grinding may now be taken up more clearly than if there were no preliminary basis of facts as to power.

Necessity for fine grinding.—The necessity for very fine grinding of the raw mixture, if a sound and volume-constant cement is to be obtained, was early stated by Newberry,* and the value of such fine grinding has been recently expressed in the quantitative form by the experiments by Professor Campbell.†

To secure a sound and volume-constant cement it is necessary that the raw mixture be very finely ground. Other things being equal, the finer the grinding of the raw mixture the better will be the resulting cement. The degree of fineness necessary to secure a given grade of cement will depend upon:

(*a*) The percentage of lime in the mixture. The higher the percentage of lime in the mixture, the finer the raw mixture must be ground, because the chances of getting an unsound or expensive cement will increase as the percentage of lime rises, and this tendency will have to be counteracted by greater fineness of grinding.

(*b*) The carefulness with which the materials have been mixed. The more careful and thorough the mixture, the less care need be bestowed upon the grinding, and vice versa.

(*c*) The character of the raw materials. This point, which has been emphasized by Newberry, is of great importance. When a very pure limestone or marl is mixed with a clay or shale, the grinding must be much finer than in the plants (such as those in the Lehigh district of Pennsylvania) where a highly argillaceous limestone (" cement rock ") is mixed with a comparatively small quantity of purer limestone. In the latter case the coarser particles of the argillaceous limestone will be so near in chemical composition to the proper mixture as to do little harm to the resulting cement, even if both the grinding and the mixing should be incompletely accomplished, while in the former case, where a pure limestone or marl is mixed with clay or shale, both of

* 20th Ann. Rept. U. S. Geol. Survey, pt. 6, p. 545.
† Journ. Am. Chem. Soc., vol. 25, p. 40 et seq.

the constituents are very different in composition from the proper mixture, and coarse particles will therefore be highly injurious to the cement.

(*d*) The duration of the burning. In the old-fashioned dome kilns, where the mixture was exposed to the action of heat for a week or more, the duration of the burning compensated in some degree for the lack of thoroughness in grinding or mixing. In modern rotary kilns, however, in which the mixture is burned for only an hour or so, this aid cannot be counted on, and both grinding and mixing must therefore be done more carefully.

Actual fineness attained.—After its final reduction, and when ready for burning, the mixture will usually run from 90 to 95 per cent through a 100-mesh sieve. In the plants of the Lehigh district the mixture is rarely crushed as fine as when limestone and clay are used. Newberry has pointed out in explanation for this that an argillaceous limestone (cement rock) mixed with a comparatively small quantity of purer limestone, as in the Lehigh plants, requires less thorough mixing and less fine grinding than when a mixture of limestone and clay (or marl and clay) is used, for even the coarser particles of the argillaceous limestone will vary so little in chemical composition from the proper mixture as to affect the quality of the resulting cement but little should either mixing or grinding be incompletely accomplished.

Bleininger * has published the results of a series of tests for fineness, made of the raw mixtures used by various plants. These results are given in table 174 following:

TABLE 174

FINENESS OF RAW MIX AT VARIOUS PLANTS. (BLEININGER.)

Cement No.	Raw Materials.	Method.	Reduced by	Residue on 80-mesh Sieve.	Residue on 120-mesh Sieve.	Residue on 200-mesh Sieve.	Diam. between 0.0088 and 0.0004 inch.	Diam. between 0.0016 and 0.0002 inch.	Diam. between 0.0011 and 0.00014 inch.	Finer than Last Size.
			Mills.							
1	Limestone and shale.	Dry	Emery	2.00	9.89	4.85	16.93	8.96	8.70	48.68
2	Cement rock and limestone.....	Dry	Griffin	16.38	11.57	4.75	16.21	13.29	7.61	30.17
3	Cement rock and limestone.....	Dry	Tube	3.03	7.42	3.68	23.77	17.52	10.26	34.33
4	Limestone and clay..	Wet	"	7.40	9.56	2.48	17.72	8.96	8.83	45.05
5	Marl and clay.....	Wet	"	3.04	5.50	5.21	20.31	12.63	9.61	44.72
6	" " "	Wet	"	30.46	4.28	2.17	6.73	10.61	9.31	47.06
7	" " "	Wet	"	2.48	5.23	2.47	16.14	14.22	12.01	47.46
8	" " "	Wet	"	26.74	6.99	2.13	10.52	9.77	7.67	36.18

* Manufacture of Hydraulic Cements, Bulletin 3, Ohio Geol. Survey.

As a matter of fact American practice at the present day has not settled down closely in this regard, though it is tending toward greater and greater fineness of the mix. Examination of results at a large number of plants using limestone mixtures shows that they vary from 82 to 96 per cent passing a 200-mesh sieve; the average, however, is probably now close to 92 per cent.

Classification of Grinding Machinery.

So many types and varieties of crushing and pulverizing machinery are now on the market that it is difficult, from a single description, to form much of an idea of the relation of any given one of these machines to any of the others. To aid in this, the machines which are used to any extent have been grouped under eight classes, according to their general methods of action. This grouping is as follows:

Class. 1. JAW CRUSHERS; material crushed between two jaws which approach and recede.....FAIRMOUNT CRUSHER, BLAKE CRUSHER.

Class 2. CONE GRINDERS; material crushed by the revolution of a toothed cone or spindle within a toothed cup.....GATES CRUSHER, CRACKERS.

Class 3. ROLLS; material crushed between two or more plain, fluted, or toothed cylinders revolving in opposite directions.....ROLLS.

Class 4. MILLSTONES; material crushed between two flat or grooved discs, one of which revolves.

MILLSTONES, BUHRS, STURTEVANT EMERY MILLS, CUMMINGS MILLS.

Class 5. EDGE-RUNNERS; material crushed in a pan, under a cylinder turning on a horizontal axis and gyrating about a vertical axis.

EDGE-RUNNERS, DRY-PAN.

Class 6. CENTRIFUGAL GRINDERS; material crushed between rollers and an annular die, against which the rollers are pressed by centrifugal force.....FULLER-LEHIGH, KENT, RING-ROLL, etc.

HUNTINGDON MILL, GRIFFIN MILL, NAROD MILL, CLARK PULVERIZER.

Class 7. BALL GRINDERS; material crushed by balls or pebbles rolling freely in a revolving horizontal cylinder.

KOMINUTER, BALL MILL, TUBE MILL.

Class 8. IMPACT PULVERIZERS; material crushed by a blow in space delivered by revolving hammers, bars, cups, or cages.

WILLIAMS MILL, RAYMOND PULVERIZER, STURTEVANT DISINTEGRATOR, STEDMAN DISINTEGRATOR, CYCLONE PULVERIZER.

All of these machines are used, at one plant or another, somewhere in the American Portland cement industry. Some of them are in very

general use; others are employed very rarely. Groups 1, 2, 6 and 7, include the more commonly used machinery; Groups 3 and 8 are some-

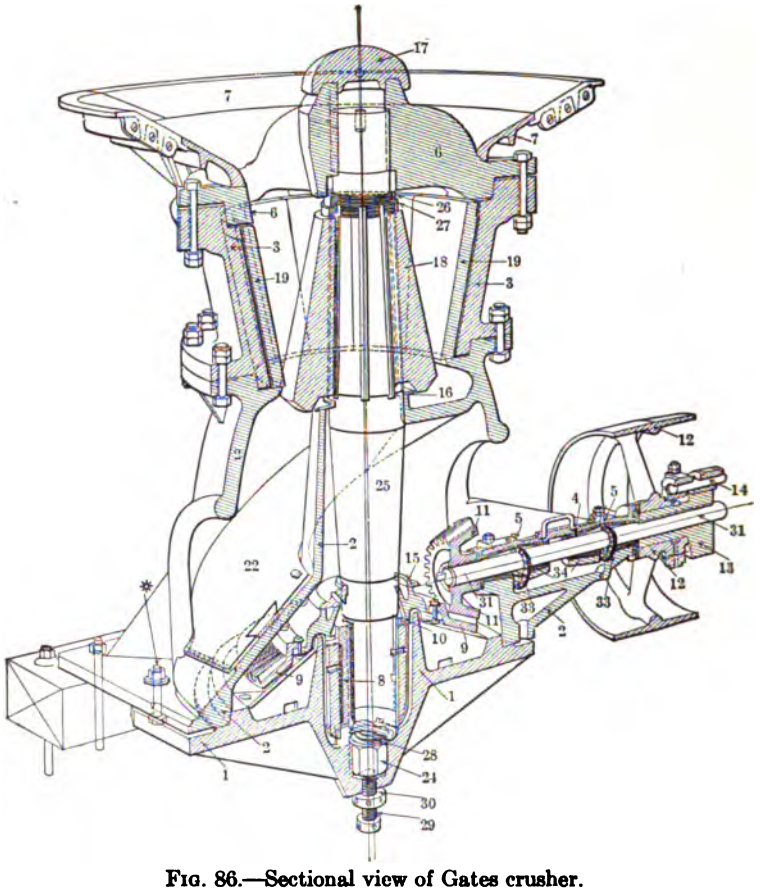


FIG. 86.—Sectional view of Gates crusher.

The names of the several parts designated by numbers in the above illustration may be found in the following table:

1. Bottom plate
2. Bottom shell
3. Top shell
4. Bearing-cap
5. Oil-cellar cap
6. Spider
7. Hopper
8. Eccentric
9. Bevel-wheel
10. Wearing-ring
11. Bevel-pinion
12. Band-wheel
13. Break-pin hub
14. Break-pin
15. Oil-bonnet
16. Dust-ring
17. Dust-cap
18. Head
19. Concaves
22. Chilled wearing-plates
24. Octagon step
25. Main shaft
26. Upper ring nut
27. Lower ring nut
28. Steel step
29. Lighter screw
30. Lighter screw, jam nut
31. Counter-shaft
33. Oiling-chain

what less used; Groups 4 and 5 include types used only in wet mixes or for clays and shales.

Modern practice, in America and elsewhere, seems to tend towards

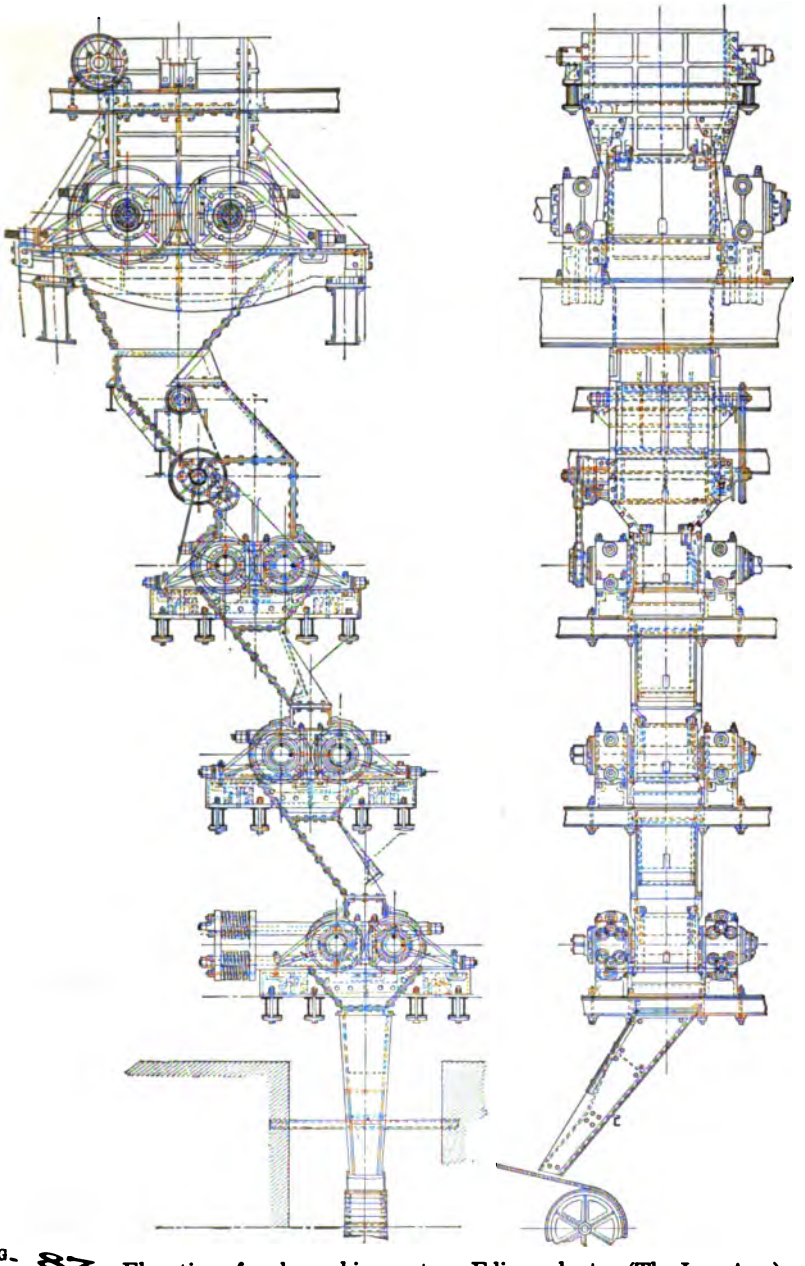


FIG. 87.—Elevation of rock-crushing system, Edison plant. (The Iron Age.)

three-stage reduction system as regards raw mix, and to somewhat less degree as regards clinker and kiln coal. In typical development we may therefore say that there will be the following stages in grinding practice;

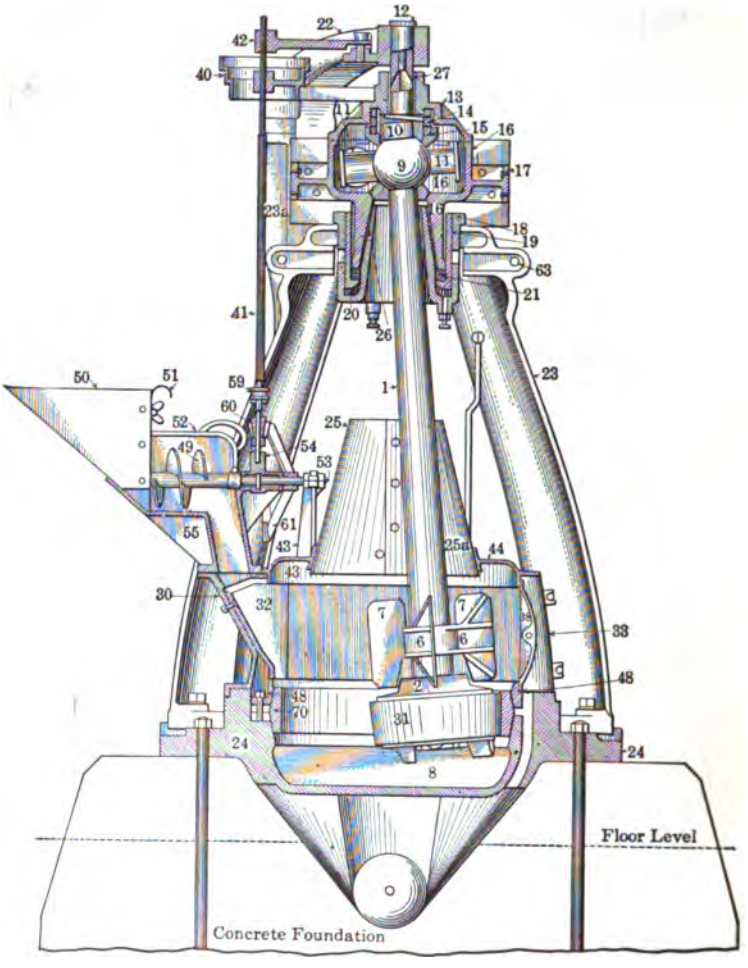


FIG. 88.—Section of Griffin mill.

(1) Reduction of quarried stone, coarse clinker or lump coal to ½ to 1-inch size; usually accomplished in a rotary or jaw crusher; sometimes by rolls.

(2) Intermediate grinding; of raw mix, clinker and coal to say 20

mesh to 60 mesh; accomplished commonly either by a Centrifugal Grinder (Group 6) or by a Ball Mill or kominuter (Group 7).

(3) Final pulverizing; accomplished either by the Tube Mill (Group 7) or by further grinding in the same Centrifugal Grinder used for the intermediate grinding; more rarely by an Impact Pulverizer (Class 8).

In the preceding chapter will be found data as to machinery actually

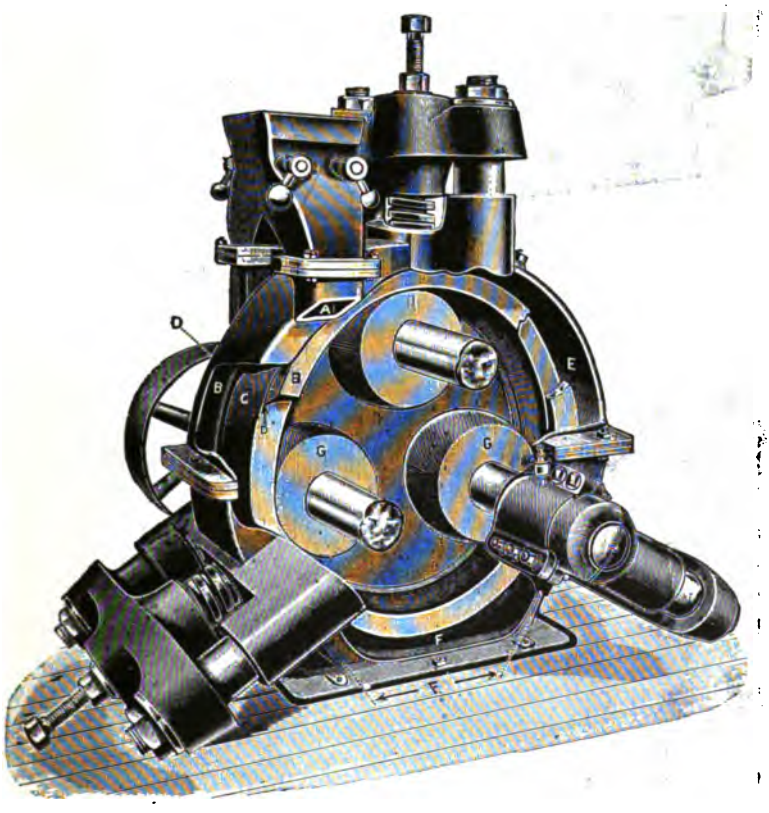


FIG. 89.—Interior of Kent mill.

installed on the raw material sides of a number of mills, both wet process and dry process. In Chapter XXXIV will be found data on the clinker-grinding practice at a number of modern mills.

Pebbles for tube mills.—The grinding work done in a tube mill was originally accomplished by means of flint pebbles. During the past few years there has been an increasing tendency to use metal slugs, in one compartment of the tube mill, and the increase in efficiency has been

FIG. 90.—Dry-pan. (Allis-Chalmers Co.)

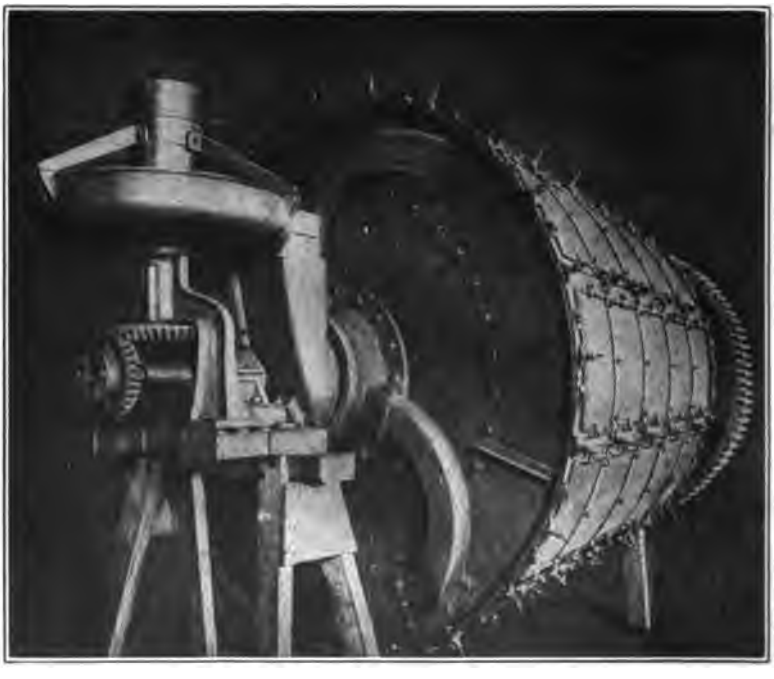


FIG. 91.—Exterior view of kominuter. (F. L. Smidth & Co.)

notable. As for the flint pebbles, which may be considered one of the minor raw materials of the cement industry, their chief supply in ordinary years was from France, Greenland, Norway, England and Denmark. Granite pebbles from the Newfoundland coast, and quartzite pebbles from the north shore of Lake Superior, have also been used to some extent.

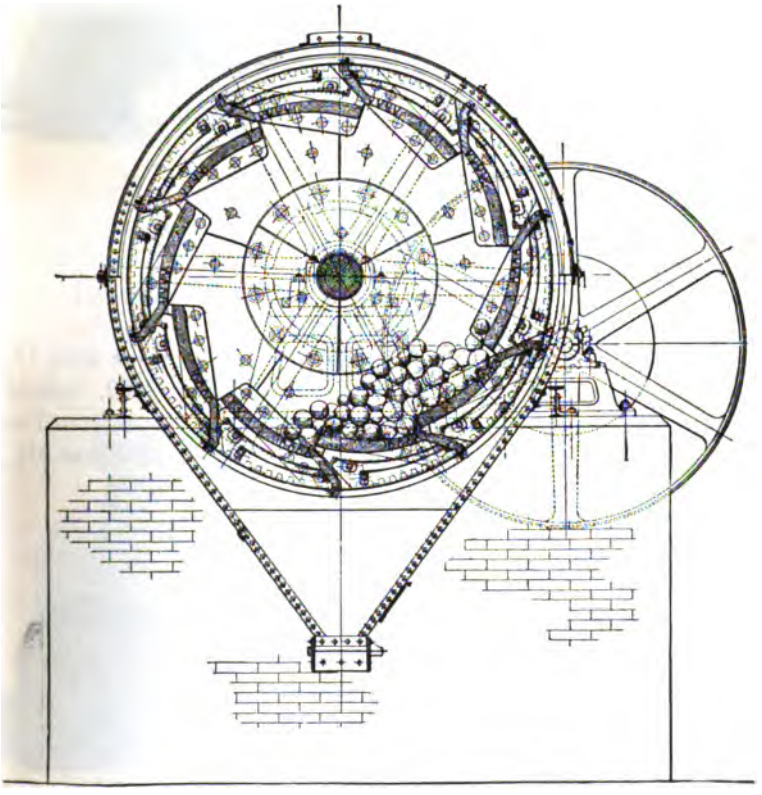


FIG. 92.—Transverse section of Gates ball mill. (Allis-Chalmers Co.)

Concerning the French flints, Mr. Thackara writes as follows:

" By the action of the sea on the base of the chalk cliffs, which form the coast-line of a portion of the Department of Seine Inférieure, fragments of the rock are detached. Those which are composed of the flint found in the cliffs, on account of their hardness, are not reduced to sand by the trituration arising from the movement of the waves or tidal currents, and become what are known as sea flint pebbles. These are gathered on the beaches between Havre and St. Valery-sur-

Somme, a distance of a little over 100 miles. Those which are nearly spherical in shape are carefully selected and are used for pulverizing cement, chemical products, etc.

FIG. 93.—Exterior view of Bonnot tube mill. (Bonnot & Co.)

" According to the official custom-house statistics, there were 13,592 tons of flint pebbles exported from France during 1900, valued at $39,248. The value of the declared exports of these stones from France to the United States for the fiscal year ended June 30, 1900, was $16,743

FIG. 94.—Gates tube mill. (Allis-Chalmers Co.)

of which $3849 were shipped from Havre, $4458 from Boulogne, and $8436 from Dieppe.

" The prices of the flint pebbles for use in the potteries range from 5s. 3d. ($1.27) to 12s. ($2.92) per ton f. o. b. in bulk at Fécamp, St. Va-

lery-en-Caux, Dieppe, Tréport, St. Valery-sur-Somme, and Havre, according to quality and to the port from which they are shipped. For the selected pebbles the prices vary from 35s. ($8.52) to 42s. ($10.21) f. o. b., packed in barrels or bags, packing included.

"The rate of freight from Havre or Dieppe to New York averages 10 francs ($1.93) per ton of 1000 kilograms (2204.6 pounds).

"French flint pebbles are shipped to England, Scotland, Norway, Sweden, Russia, Spain, Japan, and the United States. In the Baltic

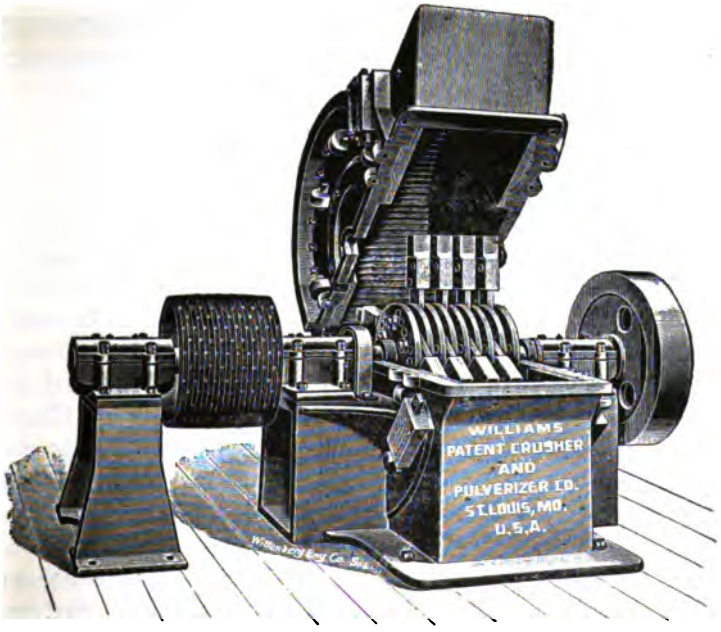


FIG. 95.—View of Williams mill, casing opened.

ports they have to compete with the pebbles exported from Denmark. Germany is now using silica sand from the river Rhine for pottery purposes, which replaces the flint pebbles. The French pebbles also have to compete with those collected on the English coast at Newhaven, Shoreham, and Rye, with the chalk flints shipped from London, and with the Greenland selected pebbles.

For the following analyses of tube-mill pebbles, from lots furnished by various importers, I am indebted to the chemists named below.

From these analyses it will be seen what large variations in composition occur in different kinds of flint pebbles. Other things being

equal, the pebbles highest in silica should give the best results, while lime is notable as suggesting physical weak zones in the pebble.

TABLE 175.

ANALYSES OF FLINT PEBBLES.

	1.	2.	3.	4.	5.	6.	7.
Silica (SiO_2)	97.16	95.20	95.00	93.05	91.50	90.20	87.00
Alumina (Al_2O_3)	0.64	3.40	3.40	6.97	2.96	10.10	13.30
Iron oxide (Fe_2O_3)							
Lime (CaO)	0.22	1.35	.....	.....	2.92	n. d.	n. d.

1. Greenland. "Dana" brand. H. S. Turner, analyst.
2. Havre, France: light. Heiberg and Roney, analysts.
3. " " dark. " " " "
4. St. Valerien, France: No. 1. " " " "
5. " " " No. 2. " " " "
6. Norway: light. " " " "
7. " : dark. " " " "

The high cost of flint pebbles for mills situated in the middle and western United States has led to many attempts to secure a domestic substitute for the expensive imported pebbles. Rounded pebbles of shape and character suitable for this use occur only on the shores of great lakes or along the beds of mountain streams. A California mill secures its supply from the American river, where rounded granite pebbles occur in quantity. These pebbles, gathered by Chinamen, cost less than $5.00 per ton at the mill, and are about half as durable as imported flints. For grinding 3000 barrels of cement, 800 lbs. of granite pebbles were used up, as against 400 lbs. of imported flint pebbles.

Flint occurs in several formations in America, but in no case do these formations outcrop along the shore, so that the flint can be obtained only in rough angular masses. Along the north shore of Lake Superior hard quartzite pebbles are known to occur in quantity, and this district and the Newfoundland coast have furnished portions of the American and Canadian pebble supply.

CHAPTER XXX.

CEMENT BURNING: FIXED KILNS.

THE preceding chapters have been devoted to a discussion of the raw materials for Portland-cement manufacture, and to the processes and methods of preparing a mixture of these materials for the kiln. In the present and following chapters the next stage of the industry will be taken up—that of burning the raw mix into cement clinker.

Fixed or Stationary Kilns.

The earliest type of kiln used in Portland-cement manufacture was a simple vertical bottle-shaped kiln closely similar to those used in the burning of lime and natural cements. This was largely succeeded by improved types of stationary kilns in Germany and France, while in the United States the rotary kiln has become standard. Though stationary kilns are now very rare in American practice they have some undoubted advantages in localities where fuel is expensive and labor is cheap. As American engineers may soon have to consider the possibility of manufacturing cement in Central and South America, where these fuel and labor conditions are fulfilled, it has been considered advisable to discuss the improved type of stationary kilns in some detail. A list of references to the more important papers on the subject is also given at the end of the chapter.

In order that the relationships of the various types of fixed or stationary kilns may be clearly understood, it will be well to group them in classes according to the general principles on which their construction and operation are based. Four such groups can be formed:

1. Dome or intermittent kilns.
2. Dome kilns with drying accessories.
3. Ring or Hoffmann kilns.
4. Continuous shaft kilns.

These classes will be described in the order named.

1. Dome or Ordinary Intermittent Kilns.

All intermittent kilns will, for convenience, be here termed dome kilns, though the term is properly restricted to intermittent kilns of one particular shape.

The dome or bottle-shaped kiln is the original form on which most fixed kilns are based. As shown in Fig. 96 it is practically the shape of the older lime-kilns, differing usually in having a somewhat greater height for a given diameter. The type shown in the figure, which is the ordinary English form, is perhaps 9 to 12 feet in diameter at its widest portion, 15 to 18 feet from its base to this widest zone, and 25 to 35 feet in total height. This kiln is usually charged at several

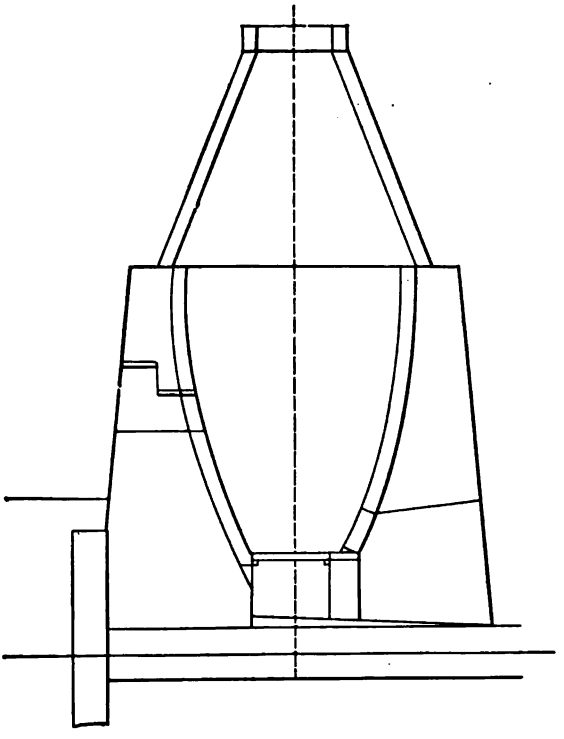


FIG. 96.—Dome kiln.

levels, one charging door being located a little below its widest point, and others being opened in the truncated cone which serves as a chimney.

In German practice these kilns assumed a form nearly like that of the blast-furnace. The body of the German dome kiln is usually a cylinder, 9 to 12 feet wide and 25 to 30 feet high. This is surmounted by a truncated-cone chimney, often high so that the total height of the kiln may be 35 to 75 feet. Candlot states that at some German plants kilns 22 feet in diameter and 100 feet in height were used, each

of which kilns would turn out 400 tons (metric) of cement for each run.

Dome kilns are charged with fuel and mix, the latter in the form of bricks, in alternate layers, the proportions varying principally with the height of the kiln and the wetness of the bricks of mix. When the kiln is full the charging doors are closed and luted with fire-clay, and the lowest layer of fuel is ignited. As the burning progresses the entire mass settles, owing to the loss in fuel and carbon dioxide. The kiln may now be refilled to its former level, but nothing is drawn from it until the burning is complete, which may take from one to two weeks. Candlot states that the production of a dome kiln varies from ½ to 1 ton of clinker for each cubic meter of burning space, and that from 23 to 30 lbs. of fuel are required per 100 lbs. of clinker, the latter quantity varying according to whether anthracite, gas-coke, or oven-coke is employed. The labor cost of charging, drawing, and picking clinker from the dome kiln may vary from 30 to 50 cents per ton of cement, equivalent to about 5 to 10 cents per barrel.

2. Dome Kilns-with Drying Accessories.

The first and simplest improvement on the primitive dome kiln was to provide each kiln with a drying tunnel. The kiln thus improved was still intermittent, but the drying tunnel gave a certain fuel economy, particularly when very wet mixes were employed. The principal type of this class of kiln is the Johnson kiln.

Johnson kiln.—The Johnson or chamber kiln was apparently the first English improvement on the simple dome kiln. It consists essentially of a dome kiln roofed over at the top, and with a long horizontal passage, semicircular in section, opening into the kiln near the top and leading to a stack. The wet slurry is placed in the horizontal passage and dried by the hot gases passing through it from the kiln to the stack. The slurry when dry must be shoveled up and charged into the kiln by hand.

Various modifications of the Johnson kiln have been suggested and used in English plants,* most of them depending for extra economy on passing the hot gases under as well as over the slurry to be dried.

The Johnson kiln, with its different modifications, may be considered essentially as combinations of old-style dome kilns and drying-floors. They utilize waste heat for drying the slurry; and are, therefore, more economical in fuel consumption than is the single-dome kiln. They

* Proc. Institution Civil Engineers, vol. 62, pp. 74–76. 1880.

are all based on intermittent working of the kiln, however; and in all, the dried slurry must be charged into the kiln by hand.

Six Johnson kilns were installed in 1890 at the plant of the Western Portland Cement Company, Yankton, S. D., but some years later were

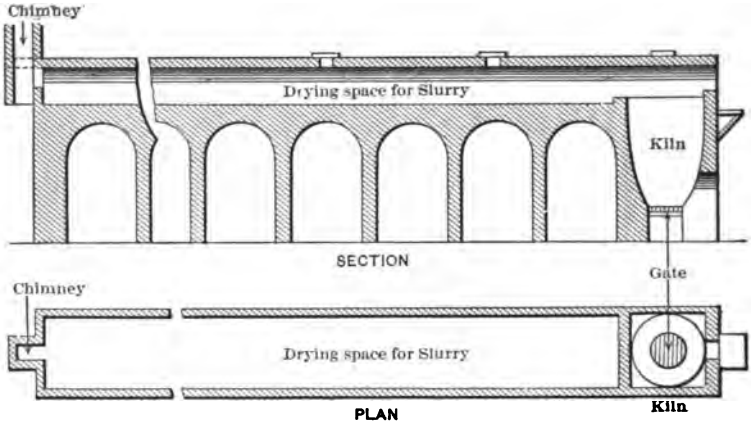


FIG. 97.—Plan and section of Johnson kiln. (Engineering News.)

replaced by rotaries. I believe that similar kilns were used in the first plant at Whitecliffs, Ark.

3. Ring or Hoffmann Kilns.

The Hoffmann or ring kiln has been used quite extensively in Germany for burning Portland cement, lime, and bricks, but has never come into favor in either England or the United States. It consists essentially of a number of chambers arranged in a circle or ellipse around a central stack. Three flues lead from each chamber to (1) the central stack, (2) the chamber preceding it in the series, and (3) the chamber following it in the series. Each of these flues may be closed at will by the insertion of a partition of sheet iron. Each chamber also has a door opening to the outside of the kiln and used for charging and drawing.

Assuming that the kiln is entirely empty (a condition which could occur only in firing up a newly built kiln), the operations would be as follows: Each chamber would be loaded with bricks of dried slurry stacked up as in a brick kiln. Slack or other fine coal is fed in at the top of the chambers and one chamber is fired. All of the flues in the kiln leading to the stack are closed except one, i.e., the flue from the chamber *behind* the one which has been fired. All the inter-chamber

flues are open except one, i.e., the flue between the fired chamber and the one immediately behind it in the series. The result of this arrangement is that the hot gases from the fired chamber pass in turn through each of the other loaded chambers until they arrive in the chamber immediately behind the fire, when they are passed into the central stack. The waste heat from the fired chamber is therefore utilized to the fullest extent in heating up all the other chambers.

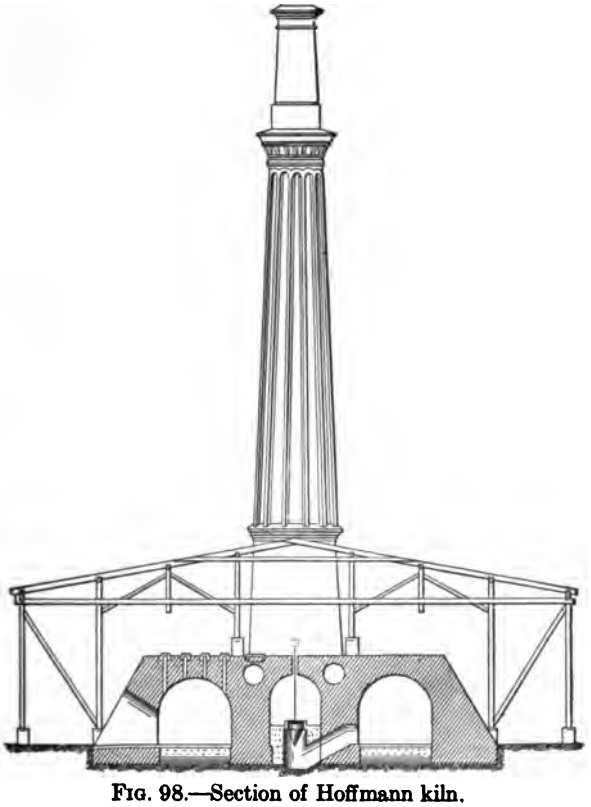


FIG. 98.—Section of Hoffmann kiln.

When the slurry in the fired chamber is converted into clinker this is allowed to cool. The chamber is then temporarily cut off from the rest of the series by closing its flues and the clinker is drawn. In the meantime the chamber next to it has been fired. The empty chamber is recharged and the flues to the central stack and *from* the chamber behind it are opened, thus making the newly filled chamber the end term of the series.

As noted, the slurry charged into a Hoffmann kiln is necessarily in the form of bricks. The expense of partly drying the slurry and molding it into bricks must, therefore, be charged against the kiln. Taken as a whole the system is low in fuel consumption, but high in labor cost, especially since skilled labor is required for all the operations. Usually one chamber is loaded and one drawn each day. The output per kiln per day will, therefore, depend on the size of the chambers.

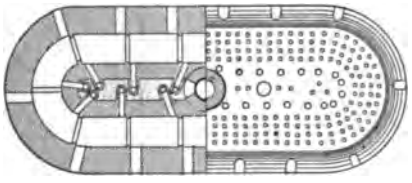


FIG. 99.—Plan of Hoffmann kiln.

4. Continuous Shaft Kilns.

Dietzsch kiln.—In 1884 the Dietzsch kiln was first used in cement-manufacture, and its advantages soon became known. It has been in use at several American plants, and in the matter of fuel consumption is, perhaps, the best type of kiln that can be employed.

Dietzsch kilns are built in pairs, back to back, as shown in Fig. 100. They are 60 to 75 feet high, and consist of a cooling chamber at the base *D*, a fire-chamber or " creuset " *C*, and a preheating chamber *A*. It will be seen that these three parts of the kiln are not all in one vertical alignment, but that the axis of the preheating chamber, though parallel to the axis of the main kiln, is off to one side some distance, so that the two portions of the structure communicate by a horizontal passage *B*.

Aalborg or Schöfer kiln.—The Aalborg kiln, soon introduced in European cement practice after the success of the Dietzsch kiln had proven the possibility of economical continuous kilns, has been used at several American plants in a more or less modified form. The kiln is shown in section in Fig. 101. It will be seen that it is essentially the same as the Dietzsch, *except* that the preheating chamber, the burning space, and the cooling chamber are all in the same vertical line. This change, slight in appearance, economizes considerably in labor, for the charge descends of itself, without the rehandling necessary in the Dietzsch kiln. The mix is introduced through the charging opening *A*, while the coal is charged through the chutes (shown in the figure about an inch below *A*).

In European practice Candlot states that an Aalborg kiln will turn

out 10 to 15 tons of clinker per day, with a fuel consumption of 280 lbs. coal per ton of product.

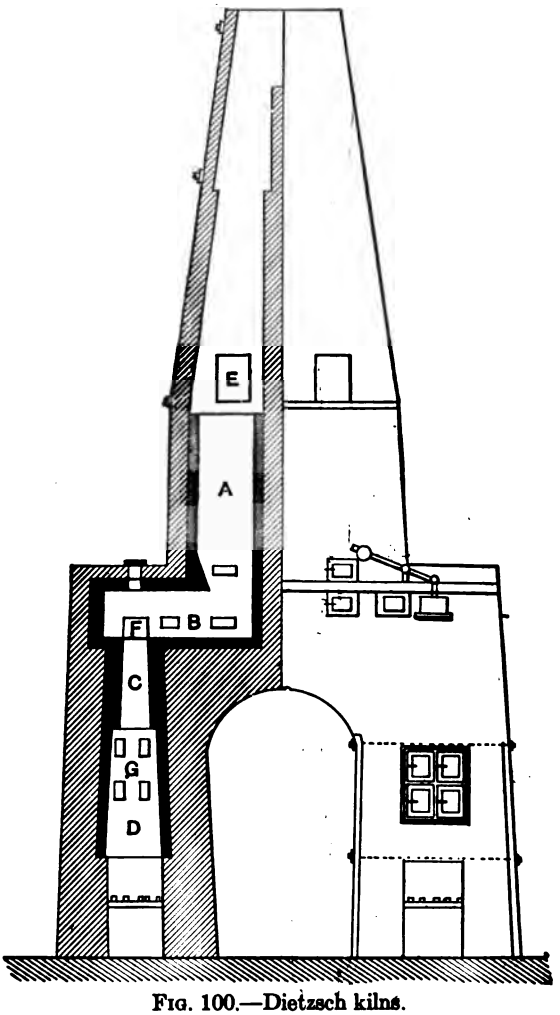


FIG. 100.—Dietzsch kilns.

Hauenschild kiln.—The Hauenschild kiln is a simple cylinder, charged at the top with both fuel and mix. It differs from a cylindrical lime-kiln only in having two distinct walls, with a space between. This annular space is used either for drying the mix or for heating the air to be supplied to the kiln. The result is that the interior lining is kept fairly cool, so that the charge does not clinker in masses against the walls,

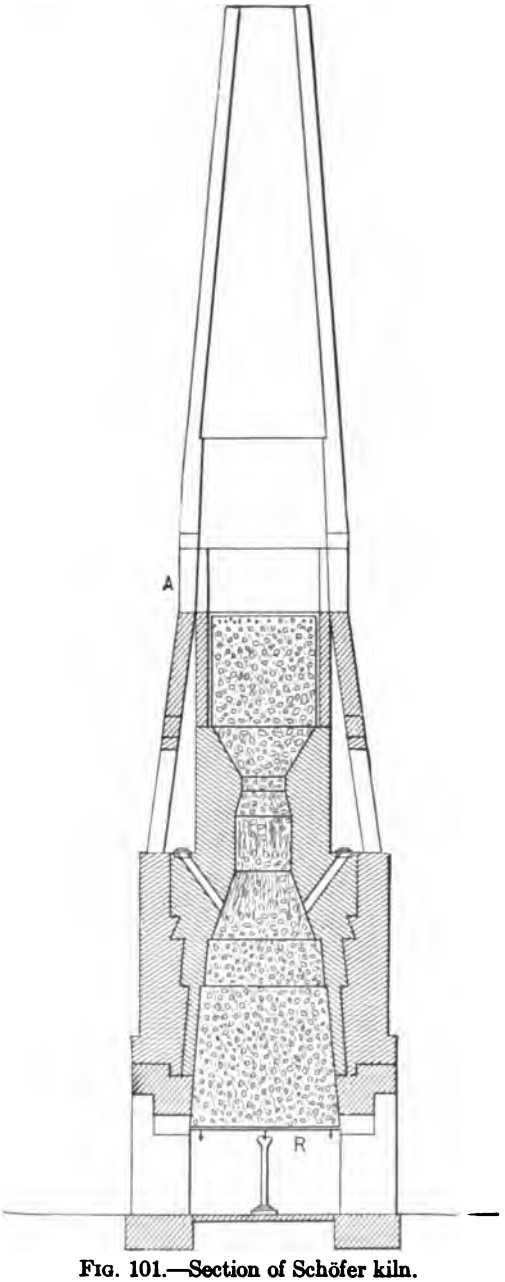


FIG. 101.—Section of Schöfer kiln.

which is the principal defect encountered in running a vertical kiln continuously.

Schwarz kiln.—In a recent paper on the manufacture of Portland cement from a mixture of slag and limestone C. von Schwarz describes a kiln used at a German cement plant. This kiln, here called the Schwarz kiln, is shown in partial section in Fig. 103. It is described as follows:

Each kiln consists, in its essential part of a series of rings, each 1 inch to 1½ inches in thickness, 8½ feet inner diameter, and 18 inches in height. These rings are provided outside with ribs, *r*, Fig. 94, and placed in such a way, one above the other, that the vertical ribs cover one another, thus forming little vertical channels *c*, *c*, *c* all around, in which the air circulates from below to the top, like in a chimney, thus continually cooling the cast-iron rings from the outside, and preventing them from getting overheated. The materials to be burnt are in direct contact

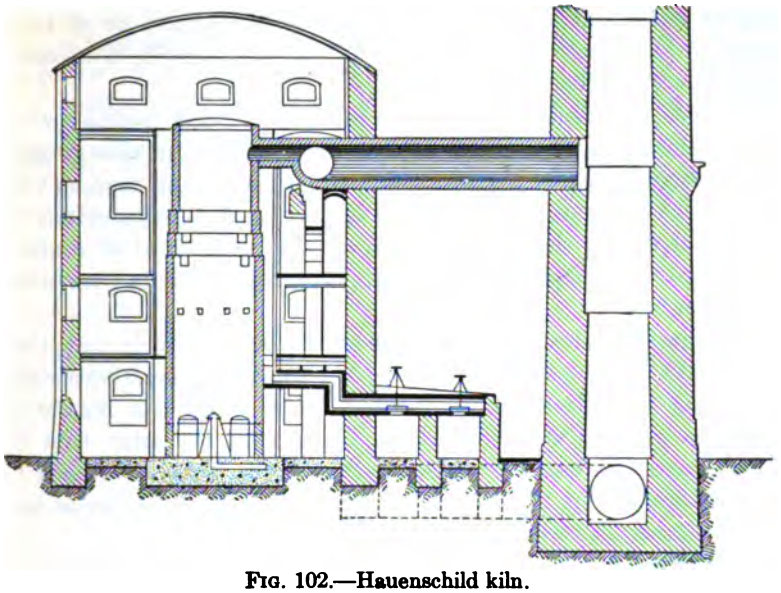


FIG. 102.—Hauenschild kiln.

with the cast-iron rings, no lining of any kind being provided for. There are 18 such rings, put one above the other, the upper rings—where the greatest heat occurs—being hooped at the joints. The top of each kiln is provided with a cone and a chimney made of sheet iron, 3 feet in diameter and 30 feet in height. The cone has four charging doors, which can be closed by sheet-iron covers as soon as the charging is done.

At a depth of 12 feet from the top the inner diameter of the kiln is lessened to nearly half its inner horizontal section, and on this zone is provided with a double row of tuyeres to admit compressed air, this arrangement having for its object to burn any carbonic oxide or carburetted hydrogen gas arising from below as completely as possible, as well as to concentrate the heat exactly where it is required, viz., on the place where the formation of the clinker is to take place.

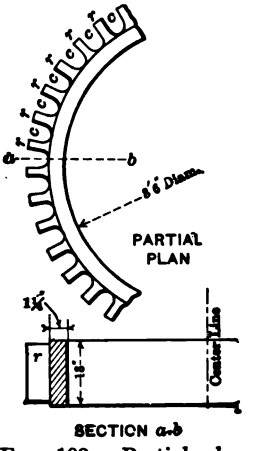


FIG. 103.—Partial plan and section of Schwarz kiln. (Engineering News.)

Compressed air is also introduced from below in two places. The pressed air is produced by a ventilator, the pressure being $\frac{3}{4}$ inch to $1\frac{1}{4}$

inches of water. One charge consists of 100 bricks and 65 to 70 lbs. of coke as fuel; one third of the coke could be replaced, if necessary, by anthracite or other small coal.

As a rule, four kilns are arranged in one set, being provided with a common elevator and a common platform, for all four kilns together. They are surrounded by a scaffolding made of angles and tees, on which the staircase to mount the platform is fixed. At the same time corrugated galvanized sheets are riveted on this scaffolding all round, in order to prevent unequal cooling of the furnaces outside in case of rain, wind, or snow.

The principal advantage of a kiln of this description is that, owing to the continuous and regular cooling from outside, the fritted clinker cannot clog the interior of the furnace, thus ensuring a regular and continuous working of the furnace. The ribs at the same time give strength, and prevent the cast-iron rings from warping. Each furnace produces about 25 tons of well-burnt clinker, equal to as much finished cement, in twenty-four hours.

Reference list for fixed kilns.—The design, construction and operation of vertical or stationary kilns of various types are discussed in many books and papers on Portland-cement manufacture. The most satisfactory of these discussions are included in the following annotated list of references on the subject:

Butler, D. B. Portland Cement: Its manufacture, testing, and use. 1899. Chapter IV of this volume, pp. 71–102, includes descriptions of the dome kiln, Johnson kiln, Batchelor kiln, Dietzsch kiln, and Hoffmann kiln. The discussion of the Johnson kiln and its modifications is particularly valuable.

Candlot, E. Ciments et chaux hydrauliques. 1898. Fixed kilns of various types are well described on pp. 53–71, inclusive.

Lewis, F. H. The Candlot oscillating grate for cement kilns. Engineering Record, May 21, 1898. Description of a grate devised to improve draft and prevent balling in shaft kilns.

Schoch, C. Die moderne Aufbereitung und Wertung der Mörtel-Materialen. 1896. Pages 124–157 of this volume contain descriptions of various improved types of fixed kilns. Those of the Hoffmann, Dietzsch, Stein, Hanenschild, and Schöfer kilns are particularly valuable.

Scott, H. S. D., and Redgrave, G. R. The manufacture and testing of Portland cement. Proc. Inst. Civ. Engrs., vol. 62, pp. 67–86. 1880.

The Johnson kiln and its modifications are described in considerable detail on pp. 74–76.

Stanger, W. H., and Blount, B. The rotatory process of cement-manufacture. Proc. Inst. Civ. Engrs., vol. 165, pp. 44–136. 1901. Valuable data

on the design, construction, and results obtained from various types of fixed kilns will be found on pp. 44, 48, 81, 82, 99, and 100.

Von Schwarz, C. The utilization of blast-furnace slag. Journal Iron and Steel Institute, 1900, No. 1, pp. 141–152. 1900. The Schwarz kiln is described with figures.

Zwick, H. Hydraulischer Kalk und Portland-Cement. 1892. Pages 148–184 are devoted to discussions of kilns and burning practice. The Hoffman ring kiln is described in great detail.

CHAPTER XXXI.

THE ROTARY KILN.

In the early days of the Portland-cement industry a simple vertical kiln, much like that used for burning lime and natural cement, was used for burning the Portland-cement mixture. These kilns, while fairly efficient so far as fuel consumption was concerned, were expensive in labor, and their daily output was small. In France and Germany they were soon supplanted by improved types, but still stationary and vertical, which gave very much lower fuel consumption. Kilns of these types have been discussed in the preceding chapter. In America,

Fig. 104.—Exterior view of rotary kiln. (Bonnot & Co.)

however, where labor is expensive while fuel is comparatively cheap, an entirely different style of kiln has been evolved. This is the rotary kiln. All American and Canadian Portland-cement plants are now equipped with rotary kilns.

The rotary kiln as at first used in cement-manufacture was adapted to dry materials only, while gas or oil were used as fuel. A long series of experiments and improvements have perfected a burning process in which finely pulverized coal is used as fuel, while wet mixtures can now be fed directly to the kiln. The present condition, in which the rotary kiln is adapted to the use of several different types of fuel, and to all kinds of Portland-cement mixtures, has been attained only through long and earnest effort on the part of American cement-manufacturers.

The history of the gradual evolution of the rotary is of great interest, but as the subject cannot well be taken up here, reference should be

made to the papers cited below,* which contain the details of this history, accompanied in many cases by illustrations of early forms of rotary kilns.

Summary of burning process.—As at present used, the rotary kiln is a steel cylinder, from 5 to 15 feet in diameter; its length for dry materials is 60 to 250 feet, while for wet mixtures an 80-foot to 265-foot kiln is commonly employed.

This cylinder is set in a slightly inclined position, the inclination being approximately one-half inch to the foot. The kiln is lined, except

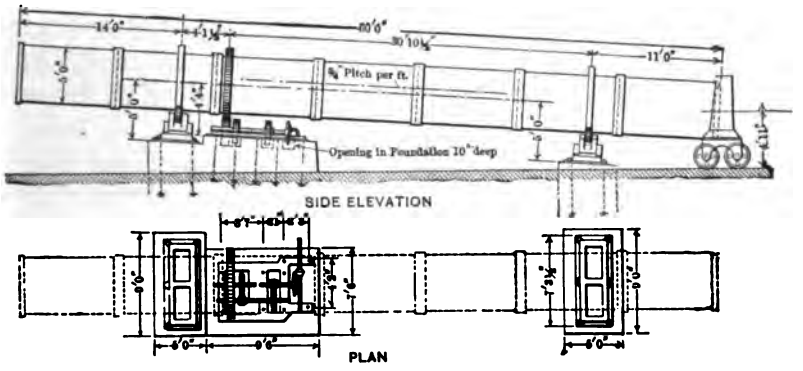


FIG. 105.—Plan and elevation of 60-foot rotary kiln. (Engineering News.)

near the upper end, with very resistant fire-brick, to withstand both the high temperature to which its inner surface is subjected and also the destructive action of the almost molten clinker.

The cement mixture is fed in at the upper end of the kiln, while fuel (which may be either powdered coal, oil, or gas) is injected at its lower end. The kiln, which rests upon geared bearings, is slowly revolved about its axis. This revolution, in connection with the inclination

* Duryee, E. The first manufacture of Portland cement by the direct rotary kiln process. Engineering News, July 26, 1900.

Eckel, E. C. Early history of the Portland-cement industry in New York State. Bulletin 44, New York State Museum, pp. 849–859. 1901.

Lesley, R. W. History of the Portland-cement industry in the United States. 8vo, 146 pp. Philadelphia, 1900.

Lewis, F. H. The American rotary kiln process for Portland cement. Cement Industry, pp. 188–199. New York, 1900.

Matthey, H. The invention of the new cement-burning method. Engineering and Mining Journal, vol. 67, pp. 555, 705. 1899.

Smith, W. A. Manufacture of cement, 1892. Mineral Industry, vol. 1, pp. 49–56. 1893.

Stanger, W. H., and Blount, B. The rotatory process of cement-manufacture. Proc. Institution Civil Engineers, vol. 145, pp. 44–136. 1901.

Editorial. The influence of the rotary kiln on the development of Portland-cement manufacture in America. Engineering News, May 3, 1900.

at which the cylinder is set, gradually carries the cement mixture to the lower end of the kiln. In the course of this journey the intense heat generated by the burning fuel first drives off the water and carbon dioxide from the mixture and then causes the lime, silica, alumina, and iron to combine chemically to form the partially fused mass known as "cement clinker." This clinker drops out of the lower end of the kiln, is cooled so as to prevent injury to the grinding machinery, and is then sent to the grinding mills.

Shape and size.—The rotary kilns in use at various plants differ considerably in both shape and size.

As to *shape*, the simplest and commonest form is that of a cylinder—a straight tube of equal diameter throughout. At many plants, however, the kilns are wider at the lower or discharge end than at the stack end. This is usually accomplished by means of a reducing section near the middle of the kiln, so that a kiln of this type might consist really of a lower section 9 feet in diameter and about 60 feet long, an upper section 8 feet in diameter and 60 feet long, and an intermediate reducing section in the shape of a frustum of a cone. The theory on which this arrangement is nominally based is that the gases, cooling as they near the upper end, should be confined in smaller space to keep up their efficiency. As against this we have, of course, the equally obvious fact that the raw mix loses its carbon dioxide as it descends the kiln, and therefore takes up less space in the lower than in the upper section.

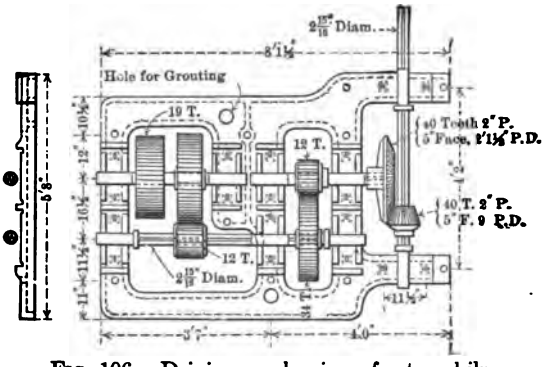


FIG. 106.—Driving mechanism of rotary kiln. (Engineering News.)

The variations in *size* are greater and more important than those in shape. Until quite recently it could be said that the standard dry-process kiln was 60 feet in length and about 6 feet in diameter, while in the wet process the length ranged from 60 to 80 feet. These lengths had become well established in practice, soon after the rotary kiln list proved successful, and for many years it seemed as if practice had become fixed in this line at least.

This lasted until Mr. Edison installed a 150-foot kiln in his New Jersey plant. The success attained by this kiln was masked for a time by defects in other portions of the plant's equipment, but as soon as it

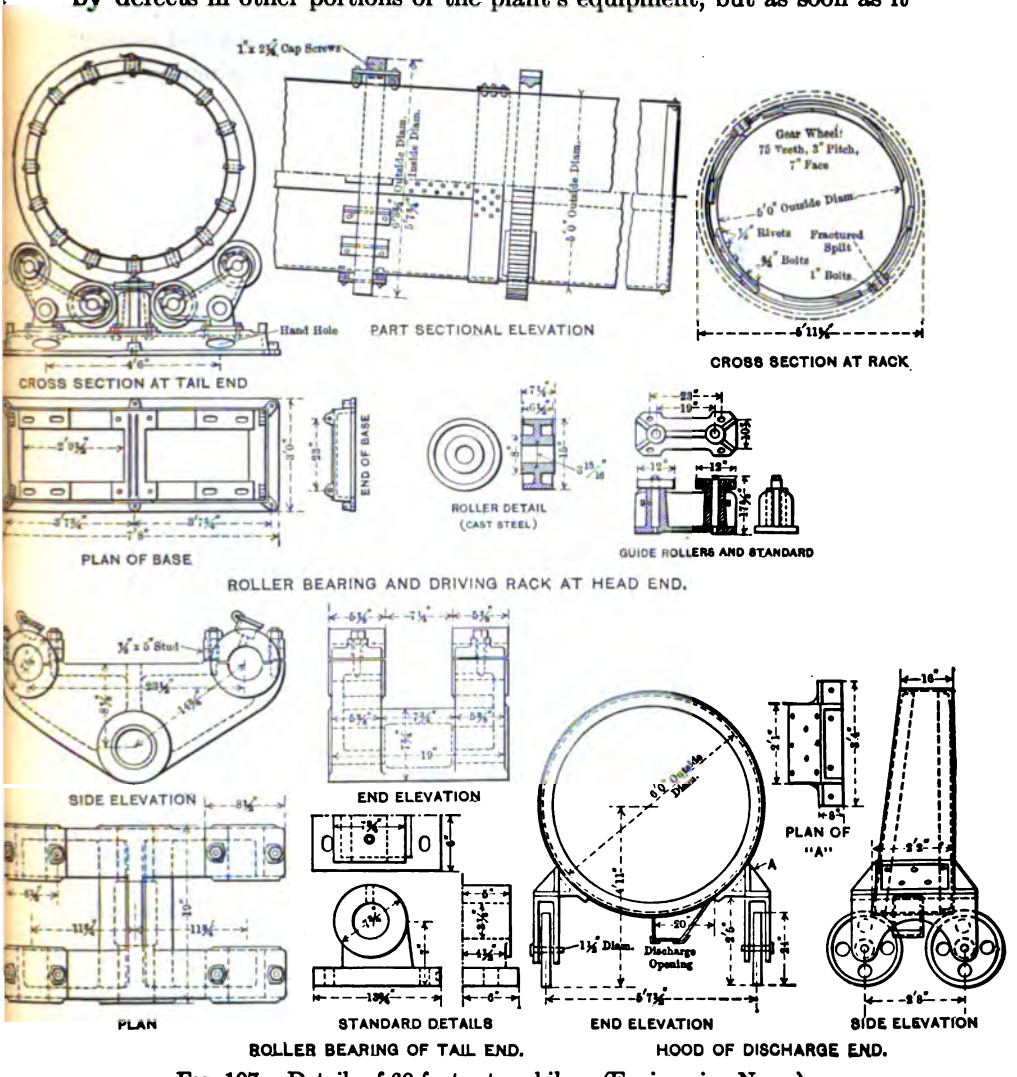


FIG. 107.—Details of 60-foot rotary kiln. (Engineering News.)

became apparent every manager in the United States began to consider the possibility of lengthening his kilns. The Edison kiln was reported to yield 350 to 375 barrels of cement per day, with a fuel con-

sumption of only 65 lbs. of coal per barrel. Sixty-foot kilns, on the other hand, usually gave 160 to 180 barrels a day when working on a dry limestone-clay mix, and might use 110 to 150 pounds of coal per barrel. In the Lehigh district, working on the easily clinkered cement rock, results were better, but even here the maximum production could

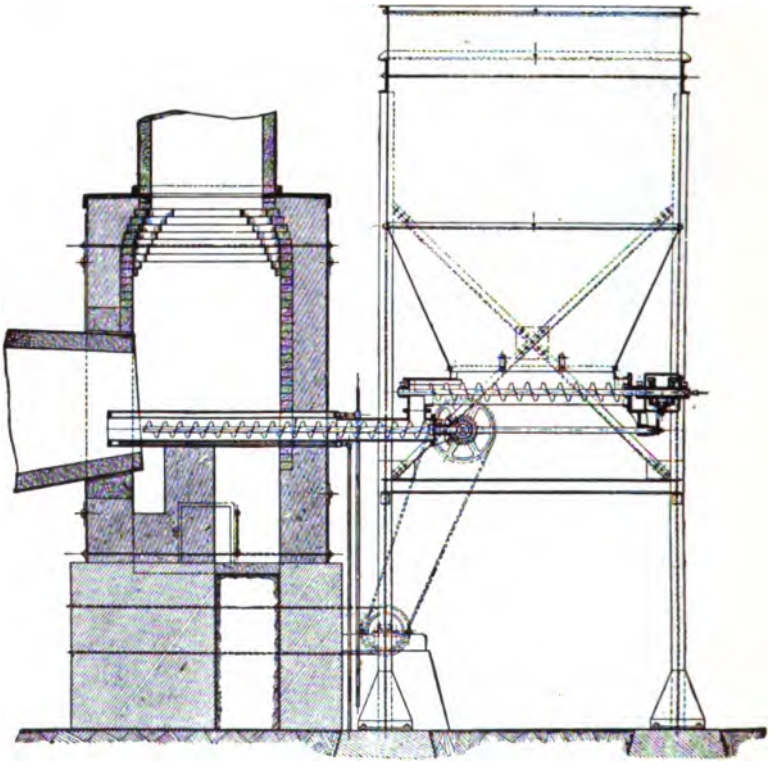


FIG. 108.—Raw material storage-bin, with adjustable feeder driven from kiln countershaft. (Allis-Chalmers Co.)

hardly exceed 225 barrels per day, with a fuel consumption perhaps as low as 95 to 120 pounds.

Such a contrast was too striking to permit much delay in lengthening kilns, and at present kilns of 135 to 175 feet in length are common, while at a few points even greater lengths are found, up to 225, 250 and 265 feet. The diameters have increased concurrently, from the old 5- or 6-foot size up to 8 or 9 feet ordinarily, and 12 or 15 feet exceptionally, in current practice.

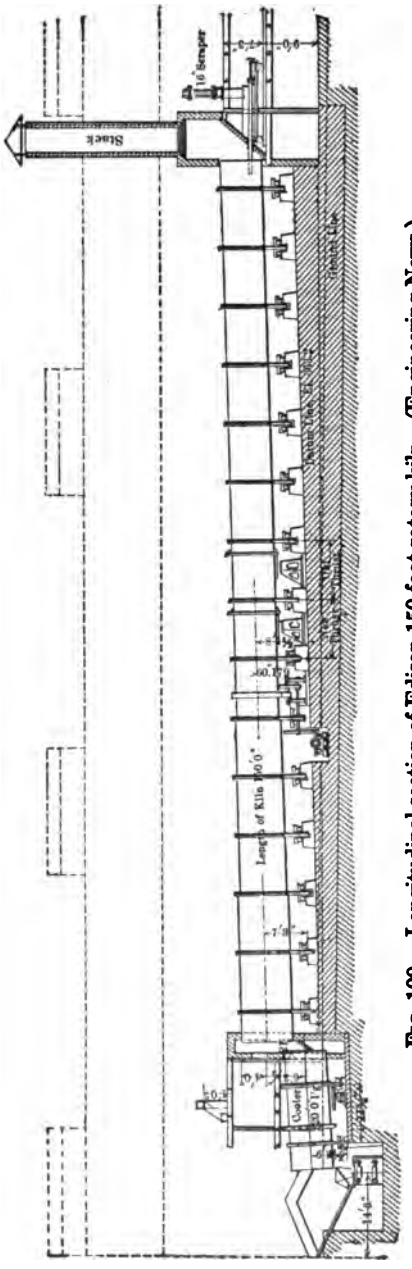
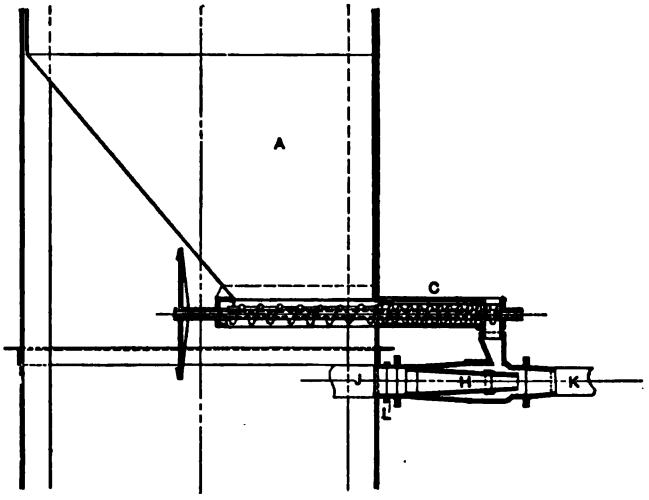
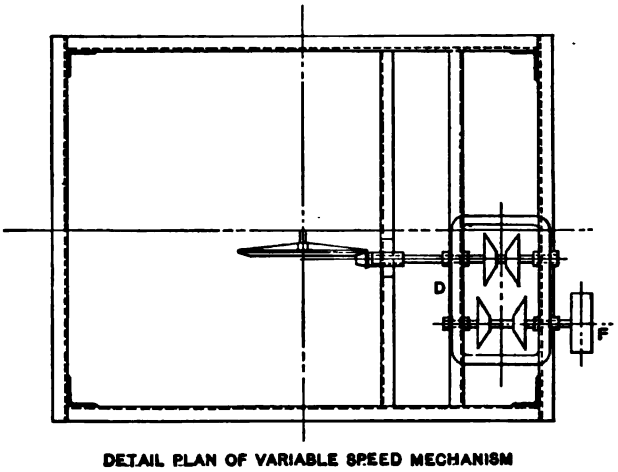


FIG. 109.—Longitudinal section of Edison 150-foot rotary kiln. (Engineering News.)

The following data, taken from Mineral Resources U. S., give the number of kilns of various lengths installed at American plants in recent periods. These are given in Table 176, page 428.



DETAIL ELEVATION OF FEEDING MECHANISM



DETAIL PLAN OF VARIABLE SPEED MECHANISM

FIG. 110.—Coal-Feeding Mechanism.

Kiln size and output.—If we disregard for the moment the question of proper burning, and think of the rotary kiln merely as a device for delivering material, it will be seen that the output of such a device will

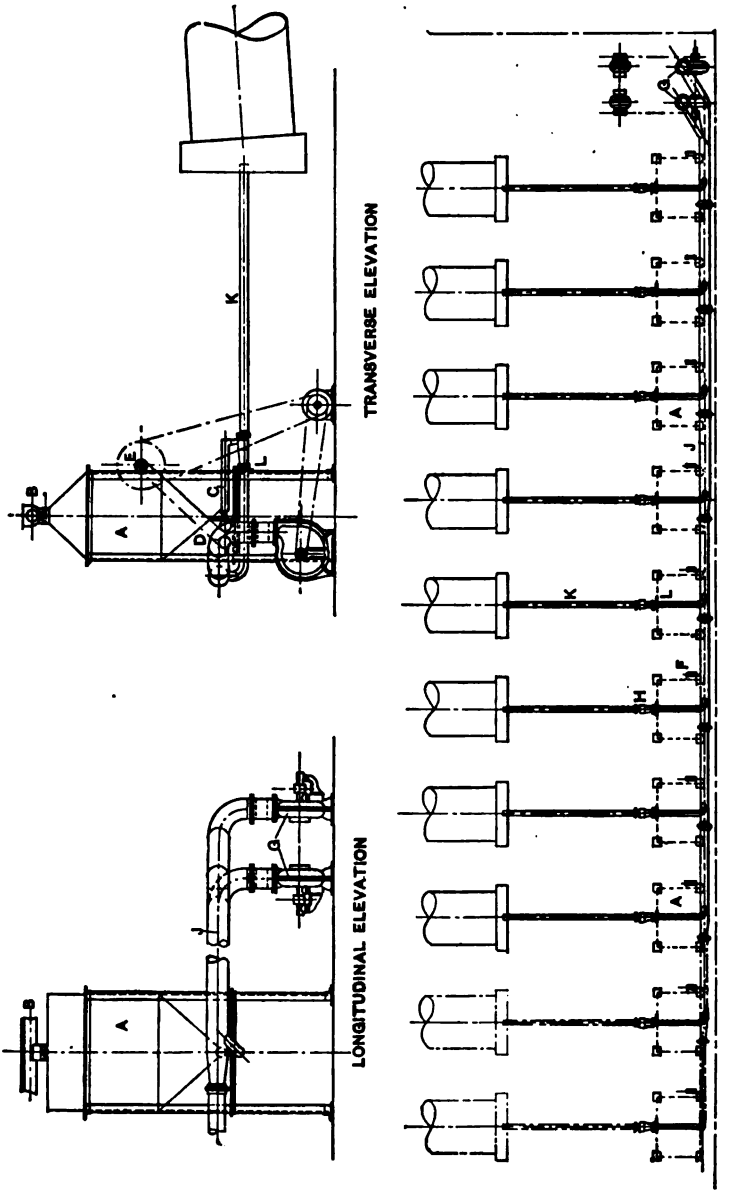

TRANSVERSE ELEVATION
LONGITUDINAL ELEVATION
PLAN
A
B
C
D
E
F
G
H
J
K
L

FIG. 111.

depend upon a number of factors. Those which affect output seriously are:

a. The internal circumference of the kiln;
b. The slope at which the kiln is set;
c. The number of revolutions at which it is revolved;
d. The condition of the interior surface;
e. The character—as to flowability—of the material carried;
f. The inclination of the upper surface of the charge.

It will be seen that the length of the kiln does not necessarily nor directly enter into the problem in any way, so long as we merely consider it mechanically. That is to say, if all other things were equal, a section of kiln 10 feet long would deliver the same output per day as a section 200 feet long.

TABLE 176.

LENGTHS OF ROTARY KILNS IN AMERICAN PLANTS.

Length (Feet).	Number of Kilns.				Length (Feet).	Number of Kilns.			
	1915.	1916.	1917.	1918.		1915.	1916.	1917.	1918.
40 to 60	99	128	108	77	126 to 149	63	62	65	63
61 to 99	124	119	94	90	150 to 199	} 47	69	73	{ 63
100 to 109	86	81	84	105	200 to 260				{ 15
110	88	89	83	65					
120	99	109	88	88		754	807	789	749
125	148	150	194	183					

But as soon as we go further with the matter, and add the requirement that the output must be properly burned, the length of the kiln does enter, as affecting this possibility, through its relation to other factors. The additional length makes it possible to use a higher inclination, to feed faster, and to revolve the kiln more rapidly—and still get a well-burned product. Factors *b*, *c*, and *f*—of the list noted above—tend therefore to vary in some fashion with the length of the kiln.

So, out of the mass of factors which directly affect kiln output, there is one—*a*—which varies directly with the circumference; there are three—*b*, *c*, and *f*—which tend to vary with the length; and there are two—*d* and *e*—which have no relation whatever to any dimension of the kiln.

If it were worth the trouble, all of the factors involved could be stated with sufficient precision to be used as a basis for a complicated but rational formula for kiln output. But for all practical purposes we may disregard this possibility, and accept the fact that, given cement mix and kiln linings as they are now, and with kiln sizes, slopes and revolutions as

in current practice, the well-burned output of a kiln will fall within the following limits:

Barrels per day $= D^2 \cdot \frac{L}{8}$ as a maximum.

Barrels per day $= D^2 \cdot \frac{L}{12}$ as a minimum.

In both cases D is the internal diameter of the discharge end of the lined kiln, in feet; L is its length, also in feet.

Kiln linings.—Various materials have been used for the linings of rotary kilns, those which have come into more or less extensive use at different points being cement clinker, high-alumina brick, bauxite brick, and various dolomite, magnesite compounds.

Of these lining materials, the use of alumina brick may be considered to be the standard American practice. In the following tables analyses of these products are given. Table 177 contains analyses of clays used in the manufacture of high-alumina kiln brick, while analyses of the brick are given in Table 178. Tables 179 and 180 contain analyses of low-alumina clays and the resulting brick, which have been supplied for rotary-kiln linings at several plants.

TABLE 177.

ANALYSES OF HIGH-ALUMINA CLAYS USED FOR KILN BRICK.

	1.	2.	3.	4.
Silica (SiO_2)	4.338	44.52	43.05	40.30
Alumina (Al_2O_3)	40.35	40.81	44.60	45.00
Iron oxide (Fe_2O_3)	0.85	1.03	2.60	n. d.
Lime (CaO)	0.88	0.62	0.40	n. d.
Magnesia (MgO)	0.23	0.55	0.20	n. d.
Carbon dioxide (CO_2) / Water	13.41	12.11	9.00	n. d.

	5.	6.	7.	8.
Silica (SiO_2)	40.80	42.71	44.00	43.52
Alumina (Al_2O_3)	49.00	38.88	42.12	42.18
Iron oxide (Fe_2O_3)	n. d.	3.36	0.86	0.42
Lime (CaO)	n. d.	0.13	0.24	0.25
Magnesia (MgO)	n. d.	0.00	0.10	0.16
Carbon dioxide (CO_2) / Water	n. d.	15.19	14.20	14.31

1, 2. Olive Hill, Carter County, Ky. Analyses from Stowe-Fuller Co.'s catalogue, p. 25½.
3, 4, 5. Hayward, Carter County, Ky. Ironton Fire-brick Co.
6. Carter County, Ky. Chas. Taylor's Sons. F. W. Clarke, analyst. Specimen selected by E. C. Eckel.
7. Lock Haven, Pa. P. L. Hobbs, analyst. Stowe-Fuller Co.'s catalogue, p. 26½.
8. " " " Crowell and Peck, analysts. Stowe-Fuller Co.'s catalogue, p. 26½.

TABLE 178.

ANALYSES OF HIGH-ALUMINA FIRE-BRICK FOR KILNS.

	1.	2.	3.	4.
Silica (SiO_2)	54.86	52.64	49.70	54.03
Alumina (Al_2O_3)	42.74	44.84	47.86	40.45
Iron oxide (Fe_2O_3)				3.47
Lime (CaO)	1.30	0.84	0.80	0.31
Magnesia (MgO)	0.62	0.88	0.80	tr.

	5.	6.	7.	8.	9.
Silica (SiO_2)	55.22	54.38	58.90	51.95	56.44
Alumina (Al_2O_3)	41.51	41.72	36.30	45.01	35.81
Iron oxide (Fe_2O_3)	.....	2.84	3.20	2.01	4.79
Lime (CaO)	.....	1.00	1.60	0.04	n. d.
Magnesia (MgO)	.....	tr.	tr.	0.29	n. d.

1, 2. "Tyrone" brick, Harbison-Walker Co. H. S. Turner, analyst.
3. Kentucky Fire Brick Co. H. S. Turner, analyst.
4. Ironton Fire Brick Co. F. W. Clarke, analyst. Specimen selected by E. C. Eckel.
5. " " " " Analysis quoted by manufacturers.
6, 7. Christy Fire Brick Co.
8. "Munro" brick, Stowe-Fuller Co. P. L. Hobbs, analyst. Catalogue, p. 70.
9. Stowe-Fuller Co. E. Davidson, analyst.

TABLE 179.

ANALYSES OF LOW-ALUMINA CLAYS USED FOR KILN BRICK.

Silica (SiO_2)	55.0	56.02
Alumina (Al_2O_3)	30.0	28.26
Iron oxide (Fe_2O_3)	tr.	2.18
Lime (CaO)	tr.	2.04
Magnesia (MgO)	tr.	0.95
Alkalies (K_2O,Na_2O)	2.0	n. d.
Carbon dioxide (CO_2) and Water	13.0	10.50

TABLE 180.

ANALYSES OF LOW-ALUMINA BRICK, FURNISHED AS KILN BRICK

	1.	2.	3.	4.	5.
Silica (SiO_2)	62.58	63.94	61.20	62.92	72.71
Alumina (Al_2O_3)	25.62	30.14	29.05	30.47	22.24
Iron oxide (Fe_2O_3)	4.76	3.70	5.55	4.61	4.47
Lime (CaO)	6.05	2.20	n. d.	n. d.	0.94
Magnesia (MgO)	0.85	tr.	n. d.	n. d.	0.42

The manner in which these bricks are set in lining kilns is shown in Figs. 112 and 113.

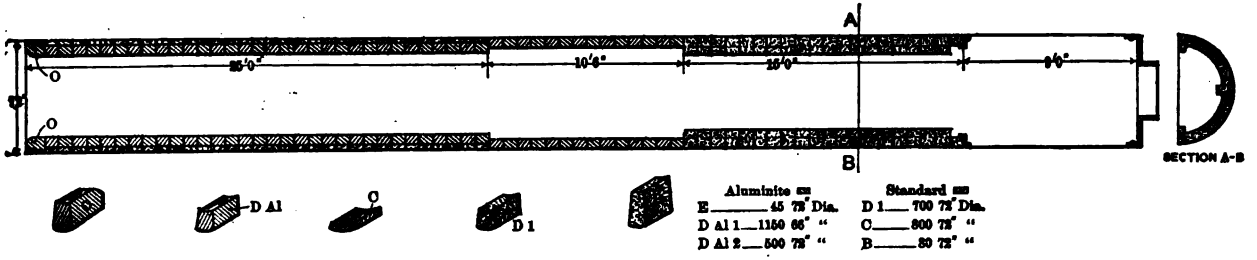


FIG. 112.—Arrangement of kiln lining, wet process. (Stowe-Fuller Co.)

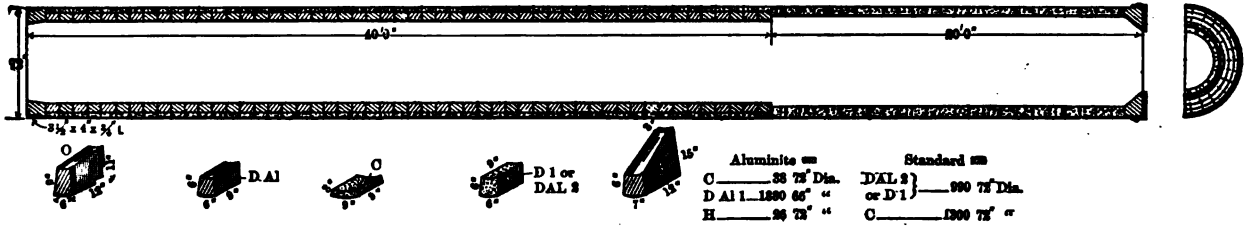


FIG. 113.—Arrangement of kiln lining, dry process. (Stowe-Fuller Co.) Asano Portland Cement Co., Tokyo, Japan.

Actual fuel consumption and output.—In the following chapter the question of heat requirements and heat distribution in the rotary kiln will be discussed in considerable detail. At present it is only necessary to state that in burning a dry mixture to a clinker, practically all of the heat consumed in the operation will be that required for the dissociation of the lime carbonate present into lime oxide and carbon dioxide. Driving off the water of combination that is chemically held by the clay or shale, and decomposing any calcium sulphate (gypsum) that may be present in the raw materials, will require a small additional amount of heat. The amount required for these purposes is not accurately known, however, but is probably so small that it will be more or less entirely offset by the heat which will be liberated during the combination of the lime with the silica and alumina. We may, therefore, without sensible error regard the total heat *theoretically* required for the production of a barrel of Portland cement as being that which is necessary for the dissociation of 450 lbs. of lime carbonate. With coal of a thermal value of 13,500 B.T.U. per pound, burned with only the air-supply demanded by theory, this dissociation would require about 25½ lbs. of coal per barrel of cement, a fuel consumption of only 6½ per cent on the weight of cement produced.

In actual practice, however, the heat required for cement production is immensely greater than that demanded by theory. This is due to the fact that heat is wasted or lost in various ways during the process of burning in the rotary kiln. The more important losses of heat occur from the fact that the stack-gases and clinker are usually discharged at high temperatures; that the air-supply injected into the kiln is always greater, and usually much greater, than that theoretically necessary; and that much heat is lost by radiation from the exposed surface of the kiln.

Sixty-foot rotary kilns are nominally rated at a production of 200 barrels per day per kiln. Even on dry materials and with good coal, however, such an output is rarely attained. Normally a 60-foot kiln working on a dry mixture will produce from 140 to 180 barrels of cement per day of twenty-four hours. In doing this, if good coal is used, its fuel consumption will commonly be from 120 to 140 lbs. of coal per barrel of cement, though it may range as high as 160 lbs., and, on the other hand, has fallen as low as 90 lbs. An output of 160 barrels per day, with a coal consumption of 130 lbs. per barrel, may therefore be considered as representing the results of fairly good practice on dry materials. With longer kilns, however, much better results are obtained, as will be noted later.

In dealing with a wet mixture, which may carry anywhere from 30 to 70 per cent of water, the results are more variable, though always worse than with dry materials. In working a 60-foot kiln or a wet material, the output may range from 80 to 140 barrels per day, with a fuel consumption of from 150 to 230 lbs. per barrel. Using a longer kiln, partly drying the mix, and utilizing waste heat will, of course, improve these figures materially.

When oil is used for kiln fuel, it may be considered that one gallon of oil is equivalent in the kiln to about 10 lbs. of coal. The fuel consumption, using dry materials, will range between 10 and 14 gallons of oil per barrel of cement; but the output per day is always somewhat less with oil fuel than where coal is used.

Natural gas in the kiln may be compared with good Pennsylvania or West Virginia coal by allowing about 20,000 cubic feet of gas as equivalent to a ton of coal. This estimate is, however, based upon too little data to be as close as those above given for oil.

The figures given in Table 181, below, are believed to be entirely reliable. They are of interest as showing what can actually be expected from kilns under average management, as distinguished from the expectations which embellish company prospectuses and the reports of "cement experts." With the exception of A, B, and J, the mills here listed are good average plants. Mill results A and B are from

TABLE 181.

ACTUAL OUTPUT AND FUEL CONSUMPTION AT VARIOUS PLANTS.

Mill.	Materials.	Process.	Per Cent of Water in Mixture.	Length of Kiln, Feet.	Output per Day, Barrels.	Coal per Barrel, Pounds.
A	Cement rock.....	Dry	..	60	225	105–113
B	" "	"	..	80	260	95–100
C	" "	"	..	60	160–180	109–175
D	" "	"	..	150	350	62–75
E	Limestone and shale.....	"	..	60	170	160
F	" " "	"	..	60	?	105
G	" " "	"	..	60	?	122
H	" " "	"	..	60	185	130
I	" " "	"	..	60	170	135
J	Marl and clay.....	Wet	60	110	135	?
K	Marl and shale.....	"	50	70	145	?
L	" " "	"	60	60	85	?
M	" " "	"	50	60	120	?
N	Marl and clay.....	"	30	60	125	173
O	" " "	"	35	60	100	160
P	" " "	"	65	60	80	180–210
Q	Limestone and clay.....	"	35	60	100	200–220
R	" " "	"	30	60	140	180

one of the best of the Lehigh district plants, while J is perhaps the best of all marl-plants. Excluding these three, it will be seen that the production per kiln per day is considerably lower, and the fuel consumption much higher, than is usually allowed for.

The differences in composition between Portland cement mixtures are very slight if compared, for example, to the differences between various natural cement rocks. But even such slight differences as do exist exercise a very appreciable effect on the burning of the mixture. Other things being equal, any increase in the percentage of lime in the mixture will necessitate a higher temperature in order to get an equally sound cement. A mixture which will give a cement carrying 59 per cent of lime, for example, will require much less thorough burning than would a mixture designed to give a cement with 64 per cent of lime.

With equal lime percentages, the cement carrying high silica and low alumina and iron will require a higher temperature than if it were lower in silica and higher in alumina and iron. But, on the other hand, if the alumina and iron are carried too high, the clinker will ball up in the kiln, forming sticky and unmanageable masses.

Fuel consumption and output, long kilns.—The preceding two pages have been allowed to stand as in the first edition of this volume, because they are fairly representative of practice with short kilns, and because we have still in service several hundred such kilns. It may be added that recent data indicate that there has not been much improvement in average practice so far as these short kilns are concerned; they do not produce much more cement than they did fifteen years ago, and they use just about as much coal per barrel of cement. The gains have come through the adoption of longer and larger kilns.

So far as output of clinker per kiln-day is concerned, these gains have been enormous. In place of the old kiln unit giving 200 barrels per day or commonly less, American practice has reached 1000 to 1500 barrels per day per kiln, with kilns 175 to 250 feet long, and 9 to 15 feet in diameter. This increased output per unit has of course brought about a decrease in the labor-cost of cement burning, but it will be well not to take that saving too seriously. It is doubtful if under the best conditions it has amounted to over one cent per barrel, for the long as against the short kiln, for average results over a long period of time.

With regard to fuel consumption, the case is more complicated, because the long kilns have shown a slight gain in economy for certain mixes and a very great gain for others. In general the dry mix shows the least gain by lengthening the kiln; it is questionable if there is any

necessary difference, between an 80- and a 200-foot kiln, of as much as 10 lbs. of coal per barrel.

With the wet mix, however, the improvement in fuel consumption due to using a long kiln reaches its maximum effect; it has been sufficient to make the wet process again a commercial possibility. With 60- or 80-foot kilns there was a tremendous difference in fuel consumption as well as in output, as between the dry and the wet mix, as is shown in Table 181. This difference tends to disappear as longer kilns are used; there is some suggestion, from the results attained by one or two American and European plants, that with kilns 200 feet and longer there is very little difference indeed between wet and dry mixes.

Factors in kiln economics.—In order to get an idea as to the trend of future progress in kiln practice, it will be well to summarize very briefly the chief economic factors which affect the solution. In doing this we will use round figures throughout; it is a matter in which any pretense at extreme accuracy becomes ridiculous.

In an earlier chapter we have seen that the heat actually needed for the chemical work done in the cement kiln amounts to less than 400,000 B.T.U. per barrel of cement—an amount which could be furnished theoretically by the consumption of not over 30 lbs. of good coal. As against this we know that at present very good practice with long kilns does not average much better than a coal supply of 80 lbs. per barrel. The gap left to fill between the possible and the actual consumption is therefore 50 lbs. of coal per barrel; with coal at $2 this amounts to five cents, with coal at $4 to ten cents per barrel of cement.

The distribution of the coal fed to the kiln, according to the work it does or the way in which it is wasted, is in current practice about as follows:

Coal used in chemical work	30 lbs.
Heat carried out by clinker	20 lbs.
Heat lost in gases and radiation	30 lbs.
Total coal supplied to kiln	80 lbs.

We have therefore three possible methods of further economy: (1) economies in the kiln itself, (2) the saving of heat at the stack, and (3) recovery of clinker heat. All of these are possible, but some are more attractive than others.

As to the kiln itself, we seem to have reached and, in many cases, passed the point of maximum fuel economy, so far as size is concerned. The data available would suggest that there is no serious gain in fuel

by using kilns over 175 feet long on a dry mix; for a wet mix this is not true, and for that we might tentatively suggest that 225 to 250-foot kilns still show some slight fuel saving over shorter lengths.

The saving of stack heat, and stack dust incidentally, seems to promise further economies; it can be best accomplished perhaps if we recur to European design, and employ a single stack for the kiln-group rather than the shorter individual stacks used in America. Along with the recovery of waste heat at this point come the related problems of saving dust and alkalies; all of which are profitable.

Recovery of clinker-heat is the most obvious of the possible economies, and it is consequently the one on which greatest progress has been made. Its advantages and its limitations are suggested elsewhere.

CHAPTER XXXII.

HEAT CONSUMPTION AND HEAT UTILIZATION.

An investigation of the ways in which the heat supplied to the kiln is utilized and wasted is a matter of both theoretical and practical importance. It can readily be seen that until some idea can be gained of the relative importance of the different causes of loss of heat, little can be done to prevent this waste or to utilize the heat so dispersed. An exact knowledge of the distribution of the total heat supplied to the kiln would therefore be of great service to the manufacturer.

In the present chapter the writer has attempted to present such data on this subject as are available, and to discuss them in such a way as to bring out the relations of the various factors in the problem of heat distribution. Attention is drawn, whenever necessary, to any doubts as to the accuracy of the data employed.

Theoretical Heat Requirements.

In order that a raw mixture shall be converted into cement clinker in the kiln, sufficient heat must be applied to bring about the necessary physical and chemical changes. The purposes for which this heat is required are:

(1) Evaporation of the water of the mix.
(2) Decomposition of the clay.
(3) Dissociation of sulphates.
(4) Dissociation of carbonates.
(5) Heating the mix to clinkering point.

Of these five requirements, it is to be noted that the first four are for accomplishing chemical changes, and that the heat supplied for these purposes is entirely absorbed in doing chemical work. This is not true with regard to the fifth requirement—the heating of the mix—for the heat used for this purpose, after it has once served its purpose, still remains as sensible and therefore utilizable heat. Most of it, in fact, passes out in the clinker.

In a perfect kiln the only heat required would be that sufficient to accomplish the first four operations in the above list, for in a theoretically perfect burning device there would be no loss by radiation, the stack-gases would be cold, and the clinker heat would be utilized.

In actual practice, however, a very large amount of heat is carried out with the stack-gases, radiated from the exposed surfaces of the kiln, and carried out in the hot clinker.

Heat utilized in evaporation of water.—It is obvious that any water contained in the charge must be evaporated, and the steam thus formed must be raised to the temperature of the stack-gases. It is here that the great difference in economy between the dry and wet methods of mixing is shown.

In the dry method the total water (mechanically held and combined) contained in the charge will rarely rise above 2½ per cent, of which about 2 per cent may be combined in the clay and ½ per cent held mechanically. The products in the dry process, when working with a 60-foot kiln, issue from the stack at a temperature of about 1500° F. =815° C. When a longer kiln is employed, and the trend of present practice seems to be in the direction of 100-foot or even longer cylinders, the stack temperatures will be correspondingly reduced. With a 100-foot kiln it seems probable that they can be kept down at least to 1000° F.

In the wet process, on the other hand, the charge usually contains about 60 per cent of water, though in a few plants this is kept down to 30 or 40 per cent. The stack temperatures are, however, much lower than in the dry process, ranging from about 800° F. with a 60-foot kiln to 450° or so in a 100-foot kiln. This partly counterbalances the loss of heat due to the high percentage of water.

Using these data as a basis, Table 182 has been prepared to show the amount of heat required for simply evaporating the water from three different types of mixture, in kilns of two different lengths.

TABLE 182.

HEAT USED IN EVAPORATION OF WATER.

Process.	Kiln Length, Feet.	Stack Temperature.	Per Cent Water.	Pounds Water per Barrel.	B.T.U. Used per Barrel.
Dry.....	60	1500° F.	2½	15	23,367
"	100	1000° F.	2½	15	21,079
Wet.....	60	800° F.	30	272	365,650
"	100	450° F.	30	272	336,630
"	60	800° F.	60	900	1,209,870
"	100	450° F.	60	900	1,113,840

Heat utilized in decomposition of clay.—An unknown, though probably small, amount of heat is required to dissociate the clayey portion of the mix. No exact data on this point are known to the writer, but the amount so utilized will probably be covered if we estimate all the water which is really chemically combined with the clay as being *mechanically held water*. This course has been followed in the present estimates. On this assumption, even a dry mix will carry about 2½ per cent of water, and this amount has been accordingly allowed for in the previous paragraph and in Table 174.

Heat utilized in dissociation of sulphates.—A certain amount of heat is taken up in dissociating any lime sulphate (gypsum) present in the raw mix. Newberry has taken this as requiring 1890 B.T.U. per pound of SO_3. In marl plants the percentage of sulphates present may rise to notable quantity, but in most other plants they are negligible. In the present discussion the assumptions will be made that the average dry mix carries 0.3 per cent of sulphur trioxide, and that the usual wet mix may carry 1 per cent. The total amount of heat required for the dissociation of sulphates will therefore be:

Dry mix..... 600 lbs. × 0.3% × 1890 = 3,402 B.T.U. per barrel
Wet mix..... " " × 1.0% × 1890 = 11,340 " " "

Heat utilized in dissociation of carbonates.—The most important heat requirement by far is that for the dissociation of the carbonates of the charge.

The values assumed by Richards for the dissociation requirements of the two carbonates are:

Liberation of 1 kilo CO_2 from $CaCO_3$ = 990 calories.
" " 1 " CO_2 " $MgCO_3$ = 407 "

These are referred to Berthelot. They correspond respectively to the two values of:

Dissociation of 1 pound $CaCO_3$ requires 784 B.T.U.
" " 1 " $MgCO_3$ " 381 "

These values will be accepted in the following calculations for the sake of uniformity, though Ostwald* quotes from Thomsen a value corresponding to 765 B.T.U. for the dissociation of 1 lb. of lime carbonate. If this latter value were accepted, the quantities given in the table below (175) should be reduced about 2½ per cent. Other values for these dissociation constants have been quoted by various authorities,

*Lehrbuch der allgemeinen Chemie, vol. II, pt. 1, p. 272.

with a much wider range, but for the present purpose those first noted will be satisfactory enough.

Temperature required for clinkering.—Widely differing statements have been made as to the temperature required in order to clinker the average Portland-cement mixture.

Carpenter, in testing the Cayuga plant noted later, determined

TABLE 183.

HEAT USED IN DISSOCIATION OF CARBONATES PER BARREL CEMENT.

Percentage MgO in Mixture.	Percentage of Lime (CaO) in Mixture.					
	40%.	41%.	42%.	43%.	44%.	45%.
	B.T.U.	B.T.U.	B.T.U.	B.T.U.	B.T.U.	B.T.U.
0	333,234	342,144	351,054	359,964	368,874	377,784
1%	338,362	347,272	356,182	365,092	374,002	382,912
2%	342,758	351,668	360,578	369,488	378,398	387,308
3%	347,154	356,064	364,974	373,884	382,794	391,704
4%	351,550	360,460	369,370	378,280	387,190	396,100

the kiln temperature by optical methods. The temperature in the kiln when working under best conditions, as determined by the Noel optical pyrometer, varied from 2250° F. near the discharge end to 2950° F. about 20 feet from the lower end, and about 1800° F. at the upper end. The temperature in the burning zone seemed to average about 2850° F., and the temperature of the entire kiln on the inside seemed to average nearly 2500° F.

For ordinary purposes of calculation, it may be assumed that 1400°–1500° C., or 2500°–2700° F., is about the necessary temperature in rotary kilns under present conditions for an average mixture. Variations in the composition of the mixture would, of course, change the clinkering point—for a low-limed high-alumina mix will clinker at a considerably lower temperature than will a mix high in lime and silica.

It is also true that to a certain degree longer exposure to the heat will be equivalent in effects to higher temperature. In stationary kilns, for example, where the charge may be exposed for days to the heat, the requisite temperature is much less than in the modern rapid practice with the rotary kiln.

Heat utilized in heating the mix.—One of the important uses of the kiln heat is in simply heating the mix up to the point at which it

will clinker. Fortunately, this can be determined with sufficient accuracy for all practical purposes.

Whatever the percentage of the water present, the dry portion of the mix will be about 600 lbs. for each barrel of cement. This 600 lbs. of material must be raised from the temperature of the air—say 60° F. —to about 1300° F. At this latter temperature the carbon dioxide, sulphur trioxide, etc., will have been driven off; and this will reduce the weight to 380 lbs. This 380 lbs. of quicklime and clay must now be raised to a temperature of about 2600° F., at which clinkering will take place.

Assuming that the above data are substantially correct, and that the specific heat of the mix is about 0.22, the heat required for the simple heating of the mix to the clinkering point can be calculated as follows:

	Per Barrel B.T.U.
600 lbs. mix heated 60° to 1300°, spec. heat 0.22 = 1260×0.22×600 =	166,320
380 " " " 1300° to 2600°, " " 0.22 = 1300×0.22×380 =	108,680
Total heat required, B.T.U.	275,000

This estimate is probably above what is actually required, for the temperatures, weights and specific heat have all been taken on the safe side. The actual heat requirements are probably close to 250,000 B.T.U. for this part of the operation.

In running an actual test of a kiln this quantity could be checked roughly by the amount of heat contained in the clinker as it leaves the kiln. In other words, a barrel of clinker carries out with it *almost* as much heat as was required to clinker the raw mix for that barrel.

As pointed out on a previous page (p. 437), the heat required for bringing the mix up to the clinkering point is not utilized in causing chemical changes, and can therefore be utilized again. In this respect it differs from the heat required for dissociating the carbonates and sulphates, decomposing the clay, etc.—for in these cases the heat is absorbed in doing chemical work and cannot be regained. For this reason it will be convenient to omit, from the total thermal requirements, the heat used in heating the mix up to the clinkering point; and to consider it rather in its *outgoing* form as heat carried out by the clinker.

Total heat requirements.—The data given in preceding pragraphs may now be conveniently summed up as in the table below. The basis for the various figures may be seen by referring back to earlier pages.

TABLE 184.

THEORETICAL HEAT REQUIREMENTS IN B.T.U. PER BARREL.

Process	Dry	Dry	Semi-wet	Wet
Water in mix	2½%	2½%	30%	60%
Stack-gases	1500° F.	1000° F.	800° F.	450° F.
	B.T.U.	B.T.U.	B.T.U.	B.T.U.
Evaporation of water	23,367	21,079	365,650	1,113,840
Dissociation of sulphates	3,402	3,402	11,340	11,340
Dissociation of carbonates	369,488	369,488	369,488	369,488
Total heat required	396,257	393,969	746,478	1,494,668
Coal theoretically necessary, lbs. per bbl.	28	28	53	107
Coal actually used, lbs. per bbl	120	85	115	150

Heat Losses in Practice.

In practice with the rotary kiln, there are a number of distinct sources of loss of heat, which result in a fuel consumption immensely greater than the theoretical requirements given above. The more important of these sources of loss are the following:

(1) The kiln gases are discharged at a temperature much above that of the atmosphere, ranging from 300° F. to 2000° F., according to the type of materials used and the length of the kiln.

(2) The clinker is discharged at a temperature varying from 200° F. to 2500° F., the range depending as before on materials and length of the kiln.

(3) The air-supply injected into the kiln is always greater, and usually very much greater, than that required for the perfect combustion of the fuel, and the available heating power of the fuel is thereby reduced.

(4) Heat is lost by radiation from the ends and exposed surfaces of the kiln.

(5) The mixture in plants using a wet process carries a high percentage of water, which must be driven off.

It is evident, therefore, that present-day working conditions serve to increase greatly the amount of fuel actually necessary for the production of a barrel of cement above that required by theory.

The extent of these losses, compared with the amount of heat actually used, can be seen from the following comparison of various estimates and tests, all relating to a 60-foot kiln on dry material:

TABLE 185.

UTILIZATION AND LOSSES OF HEAT IN ROTARY KILNS.

	Richards.	Carpenter.	Helbig.	Newberry.	Eckel.	Average.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Total heat supplied to kiln.	100.00	100.00	100.00	100.00	100.00	100.00
Heat utilized.....	19.75	23.43	25.56	25.54	23.59	23.57
Heat lost in clinker.....	10.72	14.09	12.01	15.47		13.07
Heat lost in stack-gases..	72.46	47.42	50.24	43.62	76.41	53.43
Heat lost by radiation....	−4.46	15.07	4.88	15.38		7.72
Minor heat losses.....	1.54	0.00	7.31	0.00		2.21

Heat carried out in flue dust.—A considerable amount of fine dust is carried out of the kiln by the hot gases. This flue dust, deposited wherever the air current is checked, may amount to from ½ to 3 per cent of the total amount of mix charged to the kiln.

The composition of the flue-dust is a matter of considerable industrial importance. It is composed of the lighter and finer particles of the cement mix and the ash, plus a certain amount of material deposited from the stack-gases. This last factor includes in some cases a large percentage of alkali salts, whose recovery has been developed as a profitable by-product in recent years.

Sources of Heat-supply.

To counterbalance the heat utilized and the heat wasted, as above noted, heat is *always* supplied to the kiln from two sources, and occasionally from two other sources. The invariable sources of supply are:

(1) A large and well-known supply is derived from the combustion of the fuel fed to the kiln.

(2) A smaller and very poorly defined supply is obtained from exothermic chemical combinations which take place in the kiln during clinkering.

Supplies from these two sources are necessarily received in every kiln. In addition, however, heat may be supplied from

(3) Regeneration of the clinker heat.

(4) Utilization of the heat in the stack-gases.

Heat supplied by combustion of fuel.—The most important source of the heat supplied to the kiln is, of course, the burning of the fuel injected into it. This can be estimated accurately enough, for any given kiln, if the composition of the coal and the amount of coal used per barrel of cement are known. It must be borne in mind, however, that any defects in the coal-feeding arrangements, or deficiencies in the fineness of coal grinding, should not properly be charged against

the efficiency of the kiln, but against the efficiency of the superintendent. In calculating the heat supplied to the kiln by combustion of fuel the assumption is always made that the coal is ground as fine as is economically possible, and that the injecting apparatus gives perfect combustion. Actually we know that neither of these assumptions is ever quite justified and that in some mills both are very incorrect.

If the best bituminous coal from western Pennsylvania or West Virginia be used, a theoretical heating value of 14,000 B.T.U. per lb. may be assumed: but the coals used in practice often fall very far short of this. Such a coal, used at the rate of 120 lbs. per barrel of cement, would give a heat supply of 1,680,000 B.T.U. per barrel. This is probably about equal to the *average* practice with 60-foot kilns on a dry mixture of limestone and clay. With longer kilns, under specially favorable circumstances, a fuel consumption of 90 lbs. per barrel may be expected, corresponding to a heat supply of 1,260,000 B.T.U. per barrel. With the wet process a fuel consumption of 160 lbs. per barrel is rather better than the average. This corresponds to a heat supply of 2,240,000 B.T.U. per barrel. These three estimates have therefore been used in making up the summary table.

Heat supplied by chemical combinations.—It is undoubtedly true that a considerable quantity of heat must be liberated when the lime and magnesia combine, at the clinkering temperature, with the silica, alumina and iron oxide, and that in this way considerable heat is added to that derived from the fuel. Unfortunately, however, we have no very definite knowledge as to the exact chemical combinations which taken place during clinkering, and lacking such knowledge any estimate of the amount of heat thus liberated must be considered as merely a wild guess.

Both Helbig and Richards, in the papers previously cited, have quoted Berthelot on this point as giving the following data for the heat liberated during this combination:

1 kilogram lime (CaO) liberates	530 calories
1 " magnesia (MgO) liberates	827 "

These figures, changed into English measures, are:

1 pound lime (CaO) liberates	954 B.T.U.
1 " magnesia (MgO) liberates	1489 "

For convenience these figures might be adopted in discussion, but both the reader and experimenter must bear in mind that they represent very doubtful assumptions, and are accepted merely because no better data are obtainable. In the present discussion of the subject no estimate of this type will be used.

Heat derived from the clinker.—A large part of the heat carried out in the hot clinker may be used to heat the incoming air. In Carpenter's experiments a little less than half of the clinker heat was thus utilized, but other experimenters have claimed 80 to 90 per cent efficiency for various types of clinker-heat regenerators. The amount of heat thus returned to the kiln might therefore vary from 90,000 to 175,000 B.T.U. per barrel of cement.

Heat derived from the stack-gases.—Heat may also be taken from the stack-gases and used to heat either the raw material or the air-supply. Usually, however, stack-gas heat when utilized is used in the power department of the mill rather than in the kiln.

Estimates and Tests of Heat Distribution.

Various estimates of the heat requirements of cement-manufacture have been presented by different authors, and several actual tests have been made of heat distribution in the rotary kiln. The principles on which these calculations are based have been discussed in the preceding pages, and the estimates and tests in question will now be presented for comparison.

Newberry's estimates.—Some years ago Prof. Newberry published a discussion of the question of fuel consumption which leaves little to be desired even in spite of recent changes in rotary practice. His results are summarized in Table 186.

TABLE 186.

NEWBERRY'S ESTIMATES ON HEAT DISTRIBUTION IN KILNS.

	Vertical Kiln.		Rotary Dry Process.		Rotary Wet Process.	
	B.T.U.	Per Cent.	B.T.U.	Per Cent.	B.T.U.	Per Cent.
Evaporation of water.....	14,498	3.7	20,832	3.3	827,424	59.3
Liberation of sulphates.....	11,340	2.8	11,340	1.8	11,310	0.8
Dissociation of carbonates..	344,250	88.9	344,250	54.7	344,250	24.6
Heating of mix and clinker..	.....	.....	228,000	36.3	213,312	15.3
Heating of CO_2 and SO_3 from mix.....	16,646	4.6	24,480	3.9		
Total B.T.U. required.....	386,734	100.0	628,902	100.0	1,396,326	100.0
Lbs. coal required per bbl., theoret. air-supply	31.0	.....	66.9	.....	120.0	
Lbs. coal required per bbl., 50% excess air..	32.1	.....	82.2	.....	128.7	
Lbs. coal actually used in practice.....	42–46	.....	110–120	.....	150–160	

Helbig's estimates.—Very recently Mr. A. B. Helbig has discussed this question, but only incidentally to a subject of more importance, i.e., the utilization of waste heat. Mr. Helbig's figures, slightly rearranged for convenience of comparison, will be found in Table 188 on page 449.

Results of actual tests.—It might be supposed that actual tests of the thermal efficiency of the rotary kiln could be readily made, and that the results of these tests would afford data of great value to the manufacturer. To a certain extent this is true, but, unfortunately, the results afforded by such tests require interpretation, and this in turn requires that certain chemical constants—so called by courtesy—should be employed as bases. These constants are, for example, the heat of dissociation of the carbonates and the sulphates, of the decomposition of clay, of the formation of lime silicates and aluminates, etc. The error into which most experimenters fall is to assume that these constants are quite accurately known. As a matter of fact, even the simplest of them—the heat of dissociation of lime carbonate—is given a variation of almost 50 per cent by different chemists of about equal standing; while the heats of formation of the silicates, etc., are much less certain constants.

In reporting and discussing actual tests, or in reading the reports of such tests, it must, therefore, be borne in mind that the assumptions which are necessarily made are based, in large part, on determinations of more than questionable accuracy.

Two such tests have been recently published, by Richards and Carpenter respectively, and are summarized below.

Richard's tests.—Prof. J. W. Richards tested a 60-foot rotary at the Dexter Portland Cement Company plant, Nazareth, Pa. The cement mixture and the resulting clinker are said to have had the following composition:

	Raw Mix.	Clinker.
Silica (SiO_2)	13.38	21.27
Alumina (Al_2O_3)	6.04	6.42
Iron oxide (Fe_2O_3)		3.18
Lime (CaO)	41.96	66.70
Magnesia (MgO)	1.53	2.43
Carbon dioxide (CO_2)	34.65	
Water	0.43	

The clinker " analysis " must evidently have been calculated from the raw mix, and not obtained by direct analysis.

A proximate analysis of the kiln coal—bituminous stack from Fairmount, W. Va.—gave:

Volatile matter	38.10
Fixed carbon	53.24
Ash	8.06
Moisture	0.60

"The following ultimate composition of the coal was assumed from average analyses of coal from that region of similar proximate composition.

Carbon	73.60
Hydrogen	5.30
Nitrogen	1.70
Sulphur	0.75
Oxygen	10.00
Moisture	0.60
Ash	8.05

"The kiln turns out an average of 3635 lbs. of clinkered cement per hour from 5980 lbs. of material fed to it, producing 200 lbs. of flue-dust, equal to 3.35 per cent of the weight of mixture charged. The coal used averages 110 lbs. per barrel of cement produced."

The temperature of the clinker falling out of the lower end of the kiln was measured by the Le Chatelier pyrometer, and determined to be 1200° C. = 2192° F. The temperature of the waste gases, determined 4 feet below the top of the stack, was 820° C. or 1508° F. The sensible heat in the clinker (leaving the kiln at 1200° C.) was determined by a calorimeter as 290 kilogram calories per kilo = 522 B.T.U. per pound. The waste gases in the stack analyzed as follows:

Carbon dioxide	10.2
Oxygen	11.8
Carbon monoxide	0.2
Sulphur dioxide	not determined
Water	"
Nitrogen	"

It will be noted that part of these preliminary data were determined by direct experiment, while others apparently are "averages," or otherwise of less value than experimental results. This, unfortunately, throws doubt upon some of the results obtained, as noted below. At the close of his paper, after making the necessary calculations, Mr. Richards summarized his results. This summary, recalculated to calories and B.T.U. per barrel, is presented below.

TABLE 187.

SUMMARY OF RICHARDS' TESTS OF ROTARY KILNS.

	Heat-units per Barrel.		
	Calories.	B.T.U.	Per Cent.
HEAT SUPPLY.			
Theoretical heating power of the fuel	395,000	1,567,460	84.7
Heat of combination of the clinkering materials	71,410	283,355	15.3
	466,410	1,850,815	100.0
HEAT DISTRIBUTION.			
Heat carried out by hot clinker	50,025	198,499	10.7
Heat in waste gases { in necessary products	170,000	674,560	36.1
Heat in waste gases { in excess air, etc	168,000	666,625	36.0
Heat in the flue-dust	1,056	4,190	0.2
Loss by imperfect combustion	6,124	24,300	1.3
Evaporation of water of charge	723	2,869	0.2
Dissociation of the carbonates	10,814	42,910	2.3
Loss by radiation, etc. (by difference)	59,668	236,862	12.8
	466,410	1,850,815	100.0

In regard to Richards' results it may be said that the use of such a large excess of air is not normal practice, either in the Lehigh district in general or at the Dexter plant in particular. It is further doubtful whether a kiln run so wastefully as this one appears to have been could make good cement with a fuel consumption as low as 110 lbs. per barrel. These questions throw doubt on the calculated loss of heat in the waste gases. The amount allowed for dissociation of the carbonates is apparently only about one-tenth of what should be allowed, owing to an arithmetical error. When this error is corrected, the "loss of heat by radiation" is made a minus quantity. In Table 188 below, this correction has been made, but Richards' estimates as to waste gases are left unchanged.

Carpenter's tests.—Prof. R. C. Carpenter tested two rotary kilns at the plant of the Cayuga Portland Cement Company, near Ithaca, N. Y. The test was made primarily to determine the efficiency, not of the kilns, but of a boiler designed to utilize their waste heat.

The coal used in the kilns was Westmoreland (Pa.) slack of the following composition and heating value:

Moisture	2.19
Volatile matter	32.9
Fixed carbon	54.66
Ash	10.25
B.T.U. per pound	14,022

At the time of test the two kilns were taking together 1889 lbs. coal per hour, producing 21.2 barrels of clinker, equal to a coal consumption of 89.1 lbs. per barrel. This low fuel consumption is attained in part by the use of waste heat from the clinker as shown in the table below.

Carpenter's paper, as originally published, contained a number of serious typographic errors, which the author has kindly corrected on the copy sent to me. In the table below I have therefore made use of these corrected results, so that the second column of this table (193) will be found to differ considerably from that given in the original.

It will be seen that Richards' results, when corrected for the carbonate requirements, leave no room for radiation losses.

For my own detailed estimates on most of these points, the reader is referred back to pages 438–442.

TABLE 188.

TESTS AND ESTIMATES OF HEAT DISTRIBUTION, B.T.U. PER BBL.

	Richards.	Carpenter.	Helbig.	Newberry.
Heat from combustion of coal	1,567,460	1,247,641	992,000	1,474,000
" drawn from clinker cooler	.....	96,273	149,348	
" derived from chemical combination	283,355	132,456	240,770	?
Total heat supplied	1,850,815	1,476,370	1,382,118	1,474,000
Heat used in evaporation of water	2,869	14,302	3,214	20,832
" " " dissociation of sulphates	.....	11,233	4,500	11,340
" " " dissociation of carbonates	362,524	320,253	345,625	344,250
Heat discharged in clinker *	198,499	207,999	165,942	228,000
" " " stack-gases, necessary products	674,560	700,093	694,400	462,940
Heat discharged in stack-gases, excess air	666,625			180,000
Heat discharged as CO (imperfect combustion)	24,300			
Heat discharged in flue-dust	4,190	.....	14,134	
" " by radiation, etc.	.....	222,490†	67,456‡	226,638§
Total heat distributed	1,933,567	1,476,370	1,295,271	1,474,000

* Roughly equivalent to the heat necessary to bring the mix up to the clinkering point.
† By difference.
‡ By calculation.
§ Does not check, owing in part to temperature allowances.

Heat Utilization and Economics.

Much of the heat carried out by the clinker and the stack-gases is recoverable with some ease, while that lost by radiation from the kiln is not so readily utilized. Helbig and Carpenter have described methods of waste-heat utilization in the papers cited on p. 451, to which reference should be made for further details.

Carpenter, in discussing his Cayuga tests, notes that "at the time of the test that portion of the air not supplied by the coal-feeding apparatus was forced by a special blower through the hot clinker and thence into the kiln. By this regenerative action about 80 per cent of the entering air was heated to 480° F., restoring to the *two* kilns about 2,000,000 B.T.U. per hour, or about 7 per cent of the heat produced by the combustion of the coal. The regenerator, while distinctly economical, made the clinker elevators difficult to keep in order and tended to deliver dust into the kiln-room; it also took up valuable room and after a few months of use was abandoned. The test shows, however, the value of conserving the waste heat from the clinker by heating the entering air." As the clinker of the two kilns during this test carried out 4,409,540 B.T.U. per hour, and the clinker regenerator returned 2,041,000 of this, its efficiency was 46.3 per cent.

At a German Portland-cement plant where the stack-gases are used in drying the raw materials, a large amount of very fine duts settles from the stack-gases in the drying chamber. This dust has been examined * by Seger and Kramer, and found to consist of 43.65 per cent of insoluble and 56.35 per cent of soluble matter. The insoluble matter gave: silica, 31.4 per cent; alumina, 14.7 per cent; iron oxide, 4.9 per cent; lime, 36.8 per cent; magnesia, 1.3 per cent; loss on ignition, 0.9 per cent. The soluble portion consisted of potassium sulphate 61.1 per cent, and potassium carbonate, 38.9 per cent. Calculating these proportions to percentages of the total dust, we have:

Silica (SiO_2)	13.71
Alumina (Al_2O_3)	6.42
Iron oxide (Fe_2O_3)	2.14
Lime (CaO)	16.06
Magnesia (MgO)	0.57
Potash carbonate	34.43
Potash sulphate	21.92
Loss on ignition	4 76

* Journ. Soc. Chem. Industry, vol. 23, p. 661. June 30, 1904.

The composition of this stack-dust has directed attention to the possibility of utilizing it as a source of potash, and both American and foreign patents have been taken out to cover feasible processes for this purpose.

List of references on heat requirements.—The following list contains the principal papers dealing with this phase of cement-manufacture. Those marked with an asterisk are restricted mainly to a discussion of clinkering temperatures, etc.

* Bleininger, A. V. Manufacture of hydraulic cements. Bulletin No. 3, Ohio Geological Survey, 1904.

* Campbell, E. D. Some preliminary experiments upon the clinkering of Portland cement. Journ. Amer. Chemical Soc., vol. 24, pp. 969–992, Oct., 1902.

* Campbell, E. D., and Ball, S. An experiment upon the influence of the fineness of grinding upon the clinkering of Portland cement. Journ. Amer. Chem. Soc., vol. 25, pp. 1103–1112, Nov., 1903.

* Campbell, E. D. Further experiments on the clinkering of Portland cement and on the temperature of formation of some of the constituents. Journ. Amer. Chem. Soc., vol. 26, pp. 1143–1158, Sept., 1904.

Carpenter, R. C. A test of a process for utilizing waste heat from rotary cement-kilns. Sibley Journal of Engineering, March, 1904.

Helbig, A. B. The efficiency of waste-gas boilers in connection with rotary cement-kilns. Engineering News, vol. 53, pp. 163–166, Feb. 16, 1905.

Newberry, S. B. Fuel consumption in Portland-cement burning. Cement and Engineering News, July, 1901.

Richards, J. W. The thermal efficiency of a rotary cement-kiln. Cement, vol. 5, pp. 30–35. 1904.

Trend of current practice.—During recent years attention has been directed toward recovery of heat from gases and clinker; to dust collection for its own sake; and to the treatment of kiln-dust and kiln gases for the sake of the potash contained in them. All of these are of course profitable economies, and though the end of the war has deprived kiln-made potash of most of its interest, the other lines of advance are likely to be followed in new plants.

CHAPTER XXXIII.

REQUISITES AND TREATMENT OF KILN FUELS.

THE usual fuel in rotary-kiln practice is pulverized bituminous coal. Oil, natural gas, and producer gas are, however, used at several plants. Except in the western United States, powdered coal is the normal kiln-fuel. These fuels will be discussed in the order named.

Coal.

Character of kiln coals.—In order to be suitable for use in rotary kilns the coal must be of the bituminous type, and preferably a gas-coal. Coals high in fixed carbon and low in volatile matter, while giving high temperatures, will not burn properly when pulverized and blown into the kiln, for they are slow to ignite. The anthracite and semi-bituminous coals are, therefore, ruled out, though they can be used in small quantities mixed with gas-coal, if the mixture be pulverized fine enough.

For economic reasons the kiln coal should run as low in ash as possible. The ash not only lowers the heating value of the coal, but it interferes with the composition of the mix, for much of it is always taken up by the cement during burning. The presence of sulphur, in the rotary kiln, does not hurt the cement. In any case high ash and sulphur may have to be accepted.

As shown by the analyses below, the better coals actually used range in composition about as follows:

Volatile matter	30%–40%
Fixed carbon	50%–60%
Sulphur	0%– 1½%
Ash	5%– 8%

Analyses of kiln coals.—The following table (189) of analyses of kiln coals is fairly representative of the various types of coal actually in use in rotary-kiln plants:

TABLE 189.

ANALYSES OF KILN COALS.

	1.	2.	3.	4.	5.
Volatile matter	32.90	38.10	31.38	35.41	35.26
Fixed carbon	54.66	53.24	58.23	56.15	56.33
Sulphur	n. d.	n. d.	n. d.	1.30	1.34
Ash	10.25	8.06	9.42	6.36	7.06
Moisture	2.19	0.60	1.03	2.08	1.35

	6.	7.	8.	9.	10.
Volatile matter	39.52	39.37	31.87	37.44	38.00
Fixed carbon	51.69	55.82	51.05	53.72	51.72
Sulphur	1.46	0.42	n. d.	n. d.	n. d.
Ash	6.13	3.81	5.22	5.50	5.38
Moisture	1.40	1.00	11.86	3.334	4.90

1. Westmoreland, Pa., slack, used at Cayuga Cement Co., Portland Point, N. Y. R. C. Carpenter. Cement, vol. 5, p. 1904.
2. Fairmount, W. Va., slack, used at Dexter Portland Cement Co., Nazareth, Pa. J. W. Richards. Cement, vol. 5, p. 30.
3. Fairmount, W. Va., slack, used at Alpha Portland Cement Co., Alpha, N. J. F. E. Walker, analyst.
4. West Virginia slack, used by Wolverine Portland Cement Co. at Coldwater, Mich. H. E. Brown, analyst. 22d Ann. Rep. U. S. Geol. Sur., pt. 3, p. 675.
5. West Virginia slack, used by Wolverine Portland Cement Co. at Quincy, Mich. H. E. Brown, analyst. 22d Ann. Rep. U. S. Geol. Sur., pt. 3, p. 675.
6. West Virginia slack, used by Peninsular Portland Cement Co., Cement City, Mich. J. G. Dean, analyst. 22d Ann. Rep. U. S. Geol. Sur., pt. 3, p. 675.
7. Pennsylvania slack, used by Omega Portland Cement Co., Jonesville, Mich. 22d Ann. Rep. U. S. Geol. Sur., pt. 3, p. 675.
8. Ohio coal, used by Wellston Portland Cement Co., Wellston, Ohio. W. S. Trueblood, analyst.
9, 10. Ohio coal, used by Ironton Portland Cement Co., Ironton, Ohio. C. D. Quick, analyst.

The following analyses of West Virginia kiln coals have been grouped in Table 190 as representing a long series of shipments from one field. They are typical of the better grade of our New River gas-coals. In future all our eastern industries will come to depend more and more on West Virginia coals and cokes.

TABLE 190.

ANALYSES OF KILN COALS, WEST VIRGINIA.

	1.	2.	3.	4.	5.	6.	7.
Volatile matter	40.02	41.66	39.65	39.83	42.50	37.42	40.62
Fixed carbon	53.86	52.51	54.93	51.47	55.14	51.13	53.13
Sulphur	1.97	1.86	1.62	1.99			
Ash	6.12	5.83	5.42	8.70	8.43	4.18	6.26
B.T.U.	14,225	14,352	14,510	13,836			

1, 2, 3, 4. Shipments of Gas-coal, Island Creek, New River field, W. Va. Analyses by R. E. Rosco, Chemist Virginia Portland Cement Co., Fordwick, Va.
5, 6, 7. Results on six months' shipments, same coal and analyst. Col. 5 gives highest reached by each constituent at any time; Col. 6 lowest; Col. 7 the average for entire six months.

TABLE 191.

ANALYSES OF KILN COALS, CENTRAL UNITED STATES.

	1.	2.	3.	4.	5.	6.	7.
Volatile matter	36.32	29.90	33.87	30.50	34.98	35.40	33.30
Fixed carbon	49.54	50.35	52.85	54.90	53.70	50.70	54.45
Sulphur	n. d.	n. d.	4.51	3.91	n. d.	4.38	n. d.
Ash	14.14	19.75	13.27	14.60	11.32	13.90	12.25
B.T.U	12,863	11,469	12,441	12,150	12,610	12,395	12,233

	8.	9.	10.	11.	12.	13.	14.
Volatile matter	32.15	33.97	32.12	32.59	31.19	31.71	30.59
Fixed carbon	54.60	53.65	48.48	52.80	51.04	49.21	42.39
Sulphur	4.25	4.83	3.87	1.25	2.80	1.20	3.32
Ash	13.25	12.37	19.40	10.23	12.61	12.82	16.93
Moisture	n. d.	n. d.	n. d.	3.12	2.37	5.06	6.77
B.T.U	11,990	12,484	11,628				

	15.	16.	17.	18.	19.	20.	21.
Volatile matter	32.26	30.24	31.46	29.54	29.81	30.81	31.40
Fixed carbon	44.48	45.17	44.15	45.43	45.66	44.40	43.70
Sulphur	6.10	6.02	6.19	6.19	5.80	6.14	6.03
Ash	20.07	21.19	21.43	21.68	22.25	22.66	22.60
Moisture	3.19	3.50	2.96	3.35	2.38	2.13	2.30
B.T.U	10,971	11,267	10.591	10.990	10,763	10,635	10,563

	22.	23.	24.	25.	26.	27.	28.
Volatile matter	30.81	31.45	31.19	30.31	30.35	29.30	28.35
Fixed carbon	54.94	55.65	55.70	55.69	55.77	53.54	53.93
Sulphur	2.86	2.40	2.78	3.04	3.28	3.52	3.62
Ash	9.37	8.90	10.33	9.89	9.33	11.56	12.52
Moisture	2.0	1.60	1.75	1.07	1.27	2.08	1.58
B.T.U	13,246	13,403	13,376	13,388	13,860	12,552	12,493

	29.	30.	31.	32.	33.	34.	35.
Volatile matter	32.78	32.49	33.97	33.18	34.00	33.94	34.49
Fixed carbon	47.68	50.35	46.31	46.31	46.21	45.63	45.53
Sulphur	4.42	4.40	5.29	5.32	5.62	5.12	5.23
Ash	18.34	16.10	18.76	19.24	18.27	18.85	19.08
Moisture	1.20	1.06	0.96	1.27	1.58	1.58	0.90
B.T.U	12,207	12,555					

	36.	37.	38.	39.	40.	41.	42.
Volatile matter	33.86	32.95	32.85	34.78	37.44	37.44	
Fixed carbon	46.14	46.40	52.46	49.72	50.21	55.42	
Sulphur	4.74	5.40	n. d.	n. d.	n. d.	n. d.	
Ash	18.33	19.00	11.24	13.50	8.80	3.74	
Moisture	1.67	1.65	3.45	2.00	3.55	3.40	

1–6. St. Charles, Ky.
7. Broadway, Ky.
8, 9. Luzerne, Ky.
10. Nelson, Ky. (1–10, Kosmos P. C. Co.).
11–14. West Frankfort, Ill. (Cape Girardeau P. C. Co.).
15–21. Des Moines district, Iowa. (Hawkeye P. C. Co.).
22–28. Pittsburgh, Kan. (Ash Grove P. C. Co.).
29–30. Pittsburgh, Kansas (Iola P. C. Co.).
31–37. Mineral, Kansas (Dewey P. C. Co.).
38–41. Henryetta, Okla. (Oklahoma P. C. Co.).

The analyses in Table 191 refer to kiln coals drawn from fields in Illinois, Kentucky, Iowa, Kansas and Oklahoma. They are therefore fairly representative of the average character of coal available for use to cement plants located in the central United States.

Composition of coal ash.—The composition of coal ash is a matter of serious economic importance in the cement industry, since in the rotary kiln the ash of the fuel enters, to some extent, into the composition of the mix. On the other hand, coal ash is a very useful raw material, as a corrective for over-high silica in the clays or shales available for a plant. Its use for this purpose is very limited, but it is always worth considering at plants where there is trouble of that sort.

The available published analyses of coal ash are few in number. For that reason I have asked the chemists at various plants to give me such analyses; and the more typical of these are grouped in table 192 following:

TABLE 192.

ANALYSES OF ASH OF VARIOUS AMERICAN COALS.

Number.	Silica.	Alumina.	Ferric Oxide.	Lime.	Magnesia.	SO_3.	Coal Field or District.
1	49.10	40.57		7.59	0.23	.....	Illinois; West Frankfort
2	43.5	24.7	10.8	9.56	n. d.	4.08	Iowa; Des Moines
3	44.0	33.5		10.9	n. d.	.....	Iowa; Des Moines
4	37.67	14.75	33.31	8.11	n. d.	.....	Kansas; Pittsburgh region
5	37.03	43.90		12.26	n. d.	.....	
6	36.24	14.17	40.20	7.12	n. d.	.....	
7	33.44	18.38	33.27	8.14	n. d.	.....	
8	40.70	22.13	26.32	3.52	n. d.	.....	
9	32.08	21.93	22.77	12.66	1.81	7.15	
10	25.88	11.80	25.54	13.78	1.13	.....	
11	40.20	24.65	24.65	6.35	n. d.	.....	
12	34.32	11.80	37.90	7.94	1.04	5.06	Kansas; Mineral
13	27.57	22.83		6.1	1.09	.....	Kentucky; St. Charles
14	48.32	20.07	21.89	4.52	n. d.	.....	Missouri; Bevier
15	35.06	18.60	28.00	9.72	n. d.	.....	Missouri; Cornell
16	37.67	18.45	27.70	8.55	1.06	5.43	Average of preceding 15 analyses

From the average calculated above it will be seen that coal ash, though representing clayey matter present during the deposition of the coal originally, differs very sharply from any normal clay or shale.

Disregarding the lime, magnesia, etc., which may be looked upon as accidental impurities, the relation between coal ash and ordinary clays is about as follows, expressed in terms of their silica-alumina-iron ratios:

	Silica		Alumina		Iron Oxide.
Clay or shale	6	:	2	:	1
Coal ash	4	:	2	:	3

It can be seen readily that if coal ash of this type be added either intentionally or accidentally to the mix, the result will be not only to increase the clayey component as a whole, but to change its character. It gives us, in effect, a powerful fluxing agent for an over-silicious clay or shale.

References on coal fields.—The following reports contain data on the distribution and character of the world's coal supplies in general, and on those of the United States and Canada in particular.

GENERAL. The Coal Resources of the World. 12th Inter. Geol. Congress, 4to, 3 vols. and atlas, 1256 pp. Ottawa, 1913.

CANADA. Dowling, D. B. Coal Fields and Coal Resorces of Canada. Memoir 59, Canadian Geol. Survey, 8vo, 174 pp. Ottawa, 1915.

Porter, J. B., and others. Investigation of the Coals of Canada. Canadian Dept. of Mines. 8vo, 6 vols. Ottawa, 1912.

UNITED STATES. Campbell, M. R., and others. The Coal Fields of the United States. Prof. Paper 100, U. S. Geol. Survey; in course of separate publication.

Hayes, C. W., and others. Coal Fields of the United States. 22d Ann. Report, U. S. Geol. Survey, pt. III, pp. 7–571. 1901.

Parker, E. W. Coal Fields of the United States. Mineral Resources of the U. S. for 1910, pt. II, pp. 98–242. 1911.

Crushing.—Coal may be bought in the shape of slack, lump or run-of-mine. In the former case no preliminary crushing is required, for the slack can be readily handled by ball mills, Griffin mills, or Williams mills. When slack is bought, therefore, it is sent direct to the drier and then to the fine-reducing mills. But when lump or run-of-mine are purchased the coal can profitably be crushed before being sent to the drier.

In such cases the preliminary crushing seems to be accomplished most effectually by rolls. Figs. 114 and 115 show rolls adapted to this kind of work both being made by the Allis-Chalmers Co. The rolls shown in Fig. 114 are very coarsely toothed, and are intended for use

on large lump or run-of-mine coal. They are 24″×30″ in size and can conveniently reduce large lump to about 1- or 2-inch size. In Fig. 115 a set of 24″×18″ plain-faced disintegrating rolls are shown. These will handle coal up to say, 4- to 6-inch size, and reduce it economically

FIG. 114.—Coarse, toothed rolls for lump coal. (Allis-Chalmers Co.)

to ⅜ or ½ inch. Finer than this it is hardly profitable to go, for ½-inch coal is readily dried and is of convenient size for either ball, Griffin, or Williams mills.

FIG. 115.—Rolls for coal-crushing. (Allis-Chalmers Co.)

Drying coal.—Coal, as bought, may carry as high as 15 per cent of water in winter or wet seasons; usually, it will run from 3 to 8 per cent. To secure good results from the crushing machinery it is necessary that this water should be driven off. For coal drying, as for the drying of raw materials, the rotary drier seems best adapted to American conditions. Several types of these driers are discussed on

pp. 375 and 592. It should be said, however, that in drying coal it is not safe to allow the products of combustion to pass *through* the cylinder in which the coal is being dried. This restriction serves to decrease slightly the possible economy of the drier, but an evaporation of 6 to 8 pounds of water per pound of fuel coal can still be counted on with any good drier. The fuel cost of drying coal containing 8 per cent of moisture, allowing $2 per ton for the coal used as fuel, will therefore be about 3 to 4 cents per ton of dried product.

Pulverizing coal.—Though apparently brittle enough when in large lumps, coal is a difficult material to pulverize finely. For cement-kiln use, the fineness of reduction is very variable. The finer the coal is pulverized the better results will be obtained from it in the kiln, and the poorer the quality of the coal the finer it is necessary to pulverize it. The fineness attained in practice may, therefore, vary from 85 per cent through a 100-mesh sieve to 95 per cent or more through the same. At one plant a very poor but cheap coal is pulverized to pass 98 per cent through a 100-mesh sieve, and in consequence gives very good results in the kiln.

Coal-pulverizing at American cement plants shows still very wide variations in practice as to machinery used. At a number of plants the entire pulverizing, after the first coarse grinding of the coal, is carried out in one stage, one of the high-speed reducers—like the Griffin, Huntingdon, Fuller-Lehigh or Raymond mills—being used to grind and finish the coal. At other mills a two-stage process is used, a ball mill or high-speed mill being used for reduction to say 20-mesh, and the finishing being complete in tube mills. In either case the tendency is toward finer and finer grinding of the coal, particularly in the districts where the coals obtainable are of poor grade.

Power and output in coal-grinding.—There is probably greater diversity in coal-grinding practice than in the grinding of either raw material or clinker. Grinding machines of many different types are in use; the coal reaches the plant in various sizes from slack to lump, and is ground to different finenesses. All this makes it difficult to estimate closely on the power requirements and output of the coal-grinding mill, but the following data may be of use in this connection.

A Williams mill employed at an Illinois cement-plant, working on Illinois coal from the dryer and preparing it for the tube mills, ground six tons of coal per hour to the following fineness:

Mesh of sieve.....	20	50	100	200
Per cent residue.....	6.9	43.3	76.2	87.3
Per cent passing.....	93.1	56.7	23.8	12.7

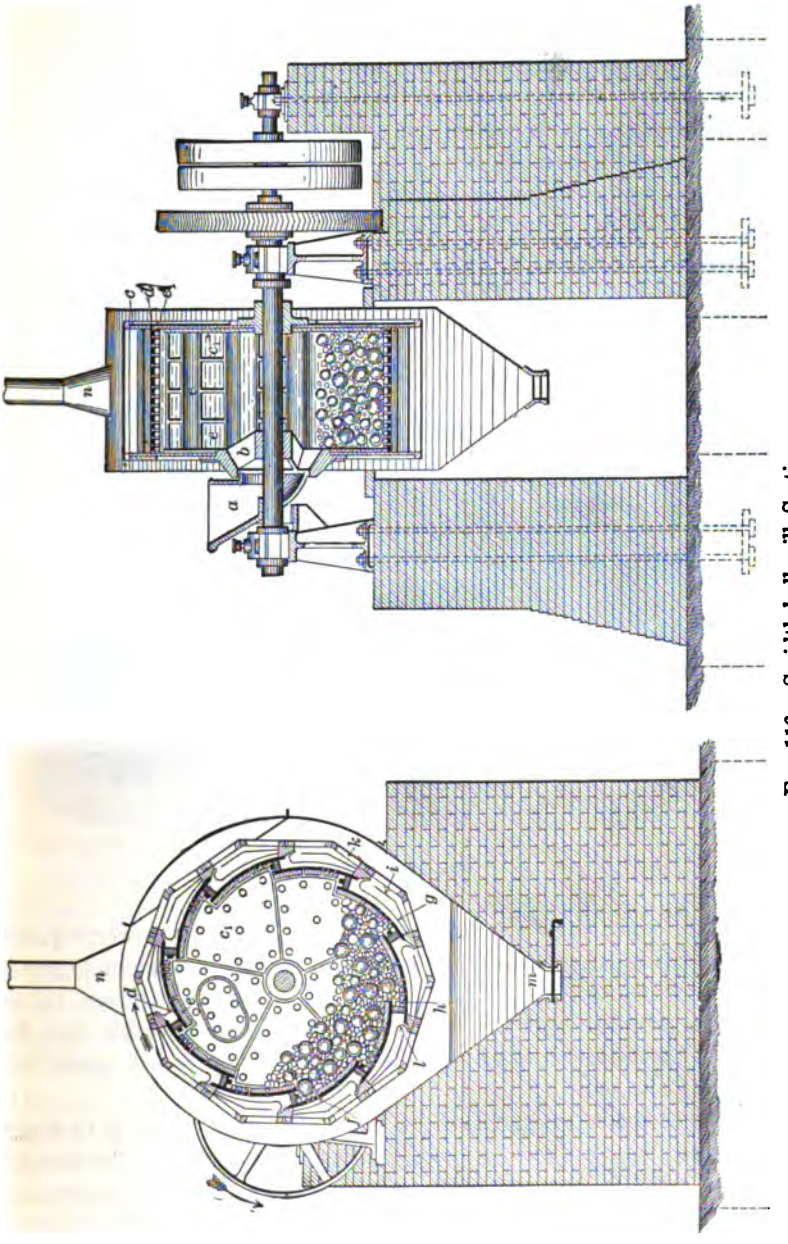


FIG. 116.—Smidth ball-mill, Section.

If the results of this test be compared with those given commonly by the same mill working on raw materials, it will be seen that coal is very readily crushed to 20-mesh, and quite easily to 50-mesh. But the percentages of coal passing the 100-mesh and 200-mesh sieves respectively are very much lower than the percentages of raw mix passing the same sieves.

A Griffin mill grinding coal from rolls or small crushers will reduce about two tons per hour to a fineness of 95 per cent through a 100-mesh screen, taking 25 to 30 H.P. in doing so.

Slack coal for three kilns is ground at one plant in a single No. 16 Davidsen tube mill, the product being about three tons per hour.

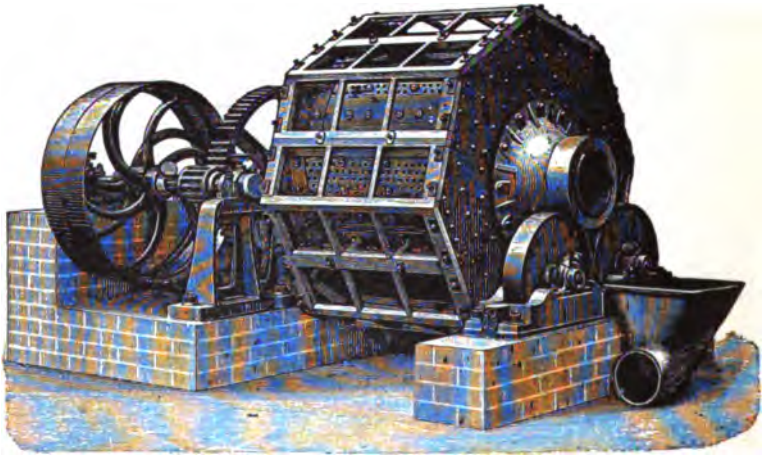


FIG. 117.—Smidth ball-mill, Exterior.

The above data show a considerable variation in the power required for coal-grinding, the performances quoted being equivalent to power consumptions of from 5 to 15 H.P. hours per ton of coal ground. If we take coarse grinding and pulverizing together, it is probable that the total power used per ton of coal reduced to kiln fineness will range from 10 to 20 H.P. hours.

Total cost of coal preparation.—The total cost of crushing (if necessary), drying, and pulverizing coal, and of conveying and feeding the product of the kiln, together with fair allowances for replacements and repairs, and for interest on the plant, will probably range from about 20 to 30 cents per ton of dried coal for four-kiln plant. This will be equivalent to a cost of from 3 to 5 cents per barrel of cement. While

this may seem a heavy addition to the cost of cement manufacture, it should be remembered that careful drying and fine pulverizing enable the manufacturer to use much poorer, and therefore cheaper, grades of coal than could otherwise be utilized.

The coal used at American plants costs from 80 cents to $2.50 per ton delivered at the mill, according to the quality of the coal and the location of the mill. These prices are of course quoted on the 1900–1915 price level.

It is probably safe to say that if a plant is so located that coal will cost over $4 per ton, and no oil or gas is obtainable, the rotary kiln is too expensive for use. Under such fuel conditions it is probably best to install stationary kilns of one of the improved designs described in Chapter XXXI. This is particularly the case in regions of low wages.

Fire and explosion risks.—The coal-handling end of the plant is subject to two quite distinct, though related, kinds of risks—from explosion and fire respectively. Precautions must be taken to guard against both of these dangers.

Explosions may occur when finely divided powdered coal is given free access to air. In order to keep as little powdered coal on hand as possible, the coal mill is usually run so as to just supply the kilns. This has some inconveniences, but it lessens the risk. During grinding care must be taken to prevent the use of exposed lights or even motors, which are apt to spark, in the coal-pulverizing building. The methods of supplying coal to the kiln should give as little access to air as possible. Separation by blowing is, of course, inadmissible, as was emphasized by the fatal results at the Edison plant in 1903.

In addition to the risk of explosion from coal-dust, there is always the chance that coal stored in bulk will heat up and cause a disastrous fire.

The following statement regarding coal storage has been recently published * by F. M. Griswold, General Inspector to the Home Insurance Company, of New York:

"The quantity stored in any one pile, heap, pocket, or bunker should in no case exceed 1500 tons. When a greater quantity must be stored there should be a clear space of at least 5 feet between the piles, and that space should be maintained absolutely free for ventilation and dispersion of gases from the mass.

"No accumulation of coal of 1500 tons or less should be piled in excess of 12 feet in height, when trimmed off, or squared, but where

* Engineering and Mining Journal, vol. 77, p. 725. 1904.

such accumulation is delivered from dump-cars on a trestle over 12 feet in height, the extreme height of the pile formed by the natural run of the coal as dumped may be 15 feet, but not more.

" Where coal is stored under shelter, there should be perfect ventilation, to facilitate escape of gas by circulation of the atmosphere.

" Wet coal, especially that wetted by snow and ice, should be disposed for immediate use; if its storage be necessary, it should be placed at the top of the pile and be spread out as thinly as practicable, in order to expedite drying.

" All accumulations of coal, large or small, should be ' rod-tested ' with frequency and regularity, in order to discover any tendency toward dangerous heating, the danger-point being set at about 160° F. If that temperature be reached, the exact locality of increasing heat may be determined by inserting an iron pipe, into which a self-registering thermometer can be lowered, allowing it to remain for sufficient time to record the full intensity of the heating."

List of references on coal drying, grinding, etc.

Bartlett, C. D. The burning of pulverized coal. Journ. Assoc. Engineering Societies, vol. 31, pp. 44–48. 1903.

Doane, A. O. The spontaneous ignition of coal. Engineering News, vol. 52, p. 141. Aug. 18, 1904.

Frazier, W. H. Fire hazards in Portland-cement mills. New York Journal of Commerce, April, 1901.

Griswold, F. M. Specifications for storage of bituminous coal. Engineering and Mining Journal, vol. 77, p. 725. 1904. Engineering News, vol. 52, pp. 409–410. Nov. 10, 1904.

Blizzard, J. Preparation, transportation and combustion of powdered coal. Bulletin 564, Canadian Dept. Mines. Ottawa, 1921.

Carpenter, R. C. Pulverized coal burning in the cement industry. Jour. Am. Soc. Mech. Engrs., Oct., 1914.

Oil.

Petroleum was early used in New York and Pennsylvania as a fuel for rotary kilns, but was gradually supplanted by powdered coal. At present no Eastern plants use oil as fuel. In the West, however, where good gas coals are unobtainable at reasonable prices, oil is now in use at four Portland-cement plants.

From 10 to 14 gallons of oil are required in Western practice to burn a barrel of cement; a safe estimate is that one barrel of oil (42 gallons) will burn three barrels of cement. Tests on long series of crude

petroleums from various fields and countries show fuel values ranging between 16,000 and 20,000 B.T.U. per pound.

List of references on petroleum.—The papers on petroleum contained in the following list are of interest either as containing discussions of the fuel value of petroleum, or as describing certain oil fields whose product is at present utilized in Portland-cement manufacture:

Bacon, R. F., and Hamor, W. A. The American petroleum industry. 8vo, 2 vols. New York, 1916.

Clapp, F. G. Petroleum and natural gas resources of Canada. 8vo, 2 vols. Canadian Dept. of Mines. Ottawa, 1914.

Emmons, W. H. Geology of petroleum. 8vo, 610 pp. New York, 1921.

Hager, D. Practical oil geology. 12mo, 253 pp. New York, 1919.

FIG. 118.—Kirkwood gas-burner.

Natural Gas.

Use of natural gas in kilns.—Natural gas has been used as a kiln fuel in several Kansas plants and at one in Ohio. As a kiln fuel it is satisfactory enough, giving as much results per B.T.U. as does a

good coal. Apparently, however, a gas-fired kiln cannot be pushed as hard as a kiln using coal, though the data are insufficient to give any decisive evidence on this point.

Analyses and thermal value.—The following analyses, made * by Prof. E. H. S. Bailey, will serve to give some idea of the composition of natural gas from a number of Kansas localities.

TABLE 193.

ANALYSES OF NATURAL GAS, KANSAS.

	Iola.	Independence.	Cherryvale.	Coffeyville.	Paola.	Osawatomie.
Hydrogen (H)	0.00	0.00	0.00	0.00	0.00	0.00
Oxygen (O)	0.45	trace	0.22	0.12	0.45	trace
Nitrogen (N)	7.76	3.28	5.94	2.21	2.34	0.60
Carbon monoxide (CO)	1.23	0.33	1.16	0.91	1.57	1.33
Carbon dioxide (CO_2)	0.90	0.44	0.22	0.00	0.33	0.22
Ethylene series (C_2H_4, etc.)	0.00	0.67	0.00	0.35	0.11	0.22
Marsh-gas (CH_4)	89.66	95.28	92.46	96.41	95.20	97.63

TABLE 194.

THERMAL VALUES OF NATURAL GAS.

State.	Field.	B.T.U. per Cubic Foot.	State.	Field.	B.T.U. per Cubic Foot.
Indiana	Anderson	1021	Pennsylvania.	East Liberty	592
"	Kokomo	1030	"	Grapeville	823
"	Marion	1024	"	"	891
"	Muncie	1019	"	Harvey	990
Kentucky	Louisville	939	"	Leechburg	1073
New York	Olean	1071	"	St. Joe	1170
" "	West Bloomfield	998	West Virginia	Fairmount	1137
Ohio	Findlay	1100	" "	Lumberport	1131
"	"	1020	" "	Morgantown	1143
"	Fostoria	1016	" "	Shinnston	1141
"	St. Mary's	1028	" "	"	1144
Pennsylvania	Cherry Tree	840	" "	"	1065
"	Creighton	1025			

* "Mineral Resources of Kansas for 1897," p. 52.

List of references on natural gas.—Of the following papers, those marked with an asterisk are of interest as discussions of the fuel value

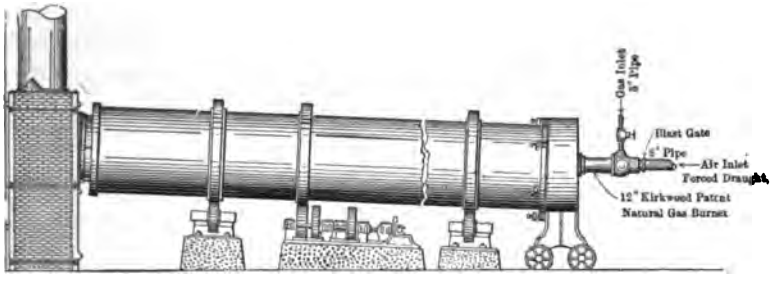


FIG. 119.—Gas-burner applied to rotary.

of natural gas, while those unmarked contain data on its utilization in the Iola district.

Adams, G. I., and others. Economic geology of the Iola quadrangle, Kansas. Bulletin 238, U. S. Geological Survey, 83 pp. 1904.

Crane, W. R. Natural gas in steam production (in Kansas). Mines and Minerals, vol. 24, pp. 154–156. Nov., 1903.

Grimsley, G. P. A new Portland-cement mill in the gas-fields of Kansas. Engineering and Mining Journal, Feb. 16, 1901.

Bailey, E. H. S. Natural gas and coal oil in Kansas. Kansas University Quarterly, vol. 4, pp. 1–14. 1895.

* Bownocker, J. A. Occurrence and exploitation of petroleum and natural gas in Ohio. Bulletin 1, 4th Series, Ohio Geol. Survey, 1903, p. 125.

* Ford, S. A. Fuel value of Pittsburg gas. American Manufacturer, supplement, April, 1886.

* Howard, C. D. Composition and fuel value of West Virginia gas. Vol. I*a*, Reports West Virginia Geol. Survey, pp. 553–556. 1904.

* Orton, E. Preliminary Report upon Petroleum and Natural Gas (in Ohio). 1887, pp. 53–54.

* Phillips, F. C. The chemical composition of natural gas. Report I, 2d Geol. Survey Penna., pp. 787–827. 1887.

* Phillips, F. C. The chemical composition of natural gas. Vol. I*a*, Reports West Virginia Geological Survey, 1904, pp. 513–552.

* White, I. C. The composition of natural gas. Vol. I*a*, Reports West Virginia Geological Survey, 1904, pp. 513–557.

Producer-gas.

Producer-gas has been used in rotary kilns at three American plants at least. Two of these plants report that their best fuel consumption,

when producer-gas was used, was equivalent to 220 to 240 lbs. coal per barrel of cement.

It is obviously uneconomical to convert a really good coal into producer-gas, merely for the sake of burning the gas in a cement kiln. But under certain circumstances the case is more promising. If good gas-coal is unobtainable, but wood or lignite are cheap, a producer-gas installation may work out satisfactorily. And in the cases, rare as yet, where the plant is being run by gas-engines, the use of producer gas in the kilns will be natural enough.

CHAPTER XXXIV.

CLINKER COOLING, GRINDING, AND STORAGE. USE OF GYPSUM.

THE clinker, issuing hot from the rotary kilns, must be very finely ground in order to convert it into cement. This involves cooling the clinker previous to grinding; otherwise the hot clinker would be difficult to handle both in transportation and in the pulverizing machinery. A third requisite of the process is that either the clinker or the ground cement must be seasoned, in some way, in order to slake any free lime that may be present. Modern clinker invariably contains some free lime, and while its effects may be masked by the free use of gypsum, it is advisable to give it as much opportunity as possible to slake and become inert.

In the present chapter, therefore, the subjects of clinker-cooling, clinker-grinding, the use of gypsum and cement storage will be taken up.

Economic Factors in Clinker Treatment

There are several distinct, though inter-related, problems which arise in connection with this final stage in cement manufacture; and it will be well to get an idea of the factors involved before going on to discussion of the methods of treatment.

It has been said above that the clinker issues hot from the kiln; that it must be ground finely; that it must be cooled in order to do this grinding cheaply; and finally that it preferably should be seasoned at some stage in the process, in order that the cement should be sound. Now all of these things are inter-related; and at least two of them can be expressed very exactly, as regards the work necessary. It will pay to do this, so that we can get an idea as to the relative importance of the different factors involved, the sort of processes that are available, and some hint as to the directions in which improvements are likely to arise profitably.

The problem, as it appears, is this:

(1) Each 370 lbs. or so (allowing for gypsum) of clinker issuing from the kiln will produce one barrel of Portland cement, after grinding.

(2) The power required for this grinding, in our mills of to-day, averages close to 8 H.P. hours per barrel of cement. To generate this amount of power will require around 40 lbs. of good coal. With coal at $2.00 per ton the power cost of clinker grinding per barrel is therefore close to four cents; with coal at $4.00 per barrel the cost will be eight cents. The labor required by the clinker grinding department will not quite double these figures ordinarily.

(3) The power needed can be reduced greatly if the clinker be thoroughly weathered before grinding; and the quality of the cement will also be improved. The most thorough way of doing this is to leave the clinker outside the mill, actually exposed to the weather, for a matter of weeks or months. It is also the cheapest way, under certain conditions; provided for example that the weathered clinker can be picked up mechanically, and that it is not frozen or left entirely too long.

(4) As against this solution, we have an important fact. The clinker issuing from the mill is hot, and much of this heat can be recovered and re-used given proper installations. Each barrel will carry out from the burning zone of the kiln (see p. 442) something like 250,000 to 275,000 B.T.U. In other words the heat so carried out by the clinker repsents some 20 lbs. of coal per barrel of cement.

The main question as to future improvements in clinker handling must be based on an adjustment between these two factors; the 40 pounds of coal, used now in grinding, and the 20 lbs. of coal represented by the heat in the clinker. The system to be preferred will save as large a fraction as possible in both these regards.

Clinker-cooling.

General methods.—Entirely aside from any question of heat-utilization, the methods of clinker cooling employed at various plants differ widely in their processes and in their effectiveness. The clinker may be simply cooled and aged by weathering, as noted above; or it may be, and more commonly is, cooled rapidly by other devices. These may be roughly grouped as follows:

Pan conveyors, rolls, and sprinkling.—At a number of plants the hot clinker is caught, as it drops out of the kiln, in pan conveyors. As

it passes along in these it is sprinkled with fine jets of water, and at some point of its progress is passed through a pair of rolls. This method, therefore, contains all the elements of any cooling system, and in a very simple form. It is not adapted to utilize the heat of the clinker, however, and the product even after sprinkling and passing the rolls is too hot to be sent immediately to the grinding-mills. The simplicity of the method is therefore counterbalanced by a loss of heat.

Stationary tower coolers.—Many plants use stationary coolers in the form of towers. The Mosser cooler, shown in section in Fig. 120,

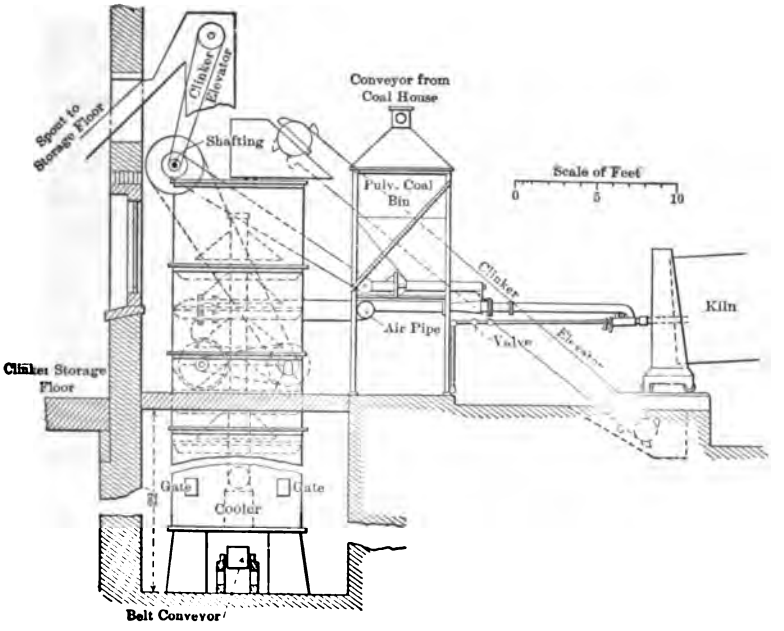


FIG. 120.—Tower cooler, Buckhorn Portland Cement Co. (Engineering News.)

is a good example of this type. The cooling installation at the Buckhorn plant is described as follows by Mr. Humphreys in Engineering News:*

"Each pair of kilns discharges through a fire-brick-lined shute into the boot of a single-chain open elevator.

"As the clinker falls into the buckets of this elevator it is sprayed with water. The elevator dumps the clinker into a cooler built by Wm. F. Mosser & Son. There are three of these coolers, each 32 feet high,

* Humphreys, R. L. The plant of the Buckhorn Portland Cement Co. Engineering News, vol. 50, pp. 408–411. Nov. 5, 1903.

8 feet in diameter, having a cast-iron blast-pipe running through the center, with sheet-steel conical shields every 5 feet, extending to within 10 inches of the shell of the cooler.

"Under this shield are holes in the blast-pipe, through which a constant flow of fresh air is maintained by means of a fan, the air passing out of the cooler through holes in its shell the latter having conical shields on the inside just above these openings.

"The heat of the clinker is absorbed in the vaporization of the water and is removed by the current of air which passes through the thin stream of clinker moving through the cooler between the two shields.

"The coolers rest on a cast-iron plate, supported by foundations 4 feet high, in a pit about 20 feet below the kiln-room floor. Running under these coolers are belt conveyors which receive the cooled clinker (drawn from four openings in each cooler) and carry it to the boot of an elevator, which discharges it through an opening in the wall between the kiln room and the clinker ball-mill department onto a storage floor."

One-stage rotary cooler.—The next step in clinker-cooling devices is the use of rotary coolers. These are simply rotary driers, reversed in action, and require no special description here. They may be readily adapted to recovery of a large fraction of the heat carried in the clinker.

Atlas two-stage rotary cooler.—By far the most satisfactory of cooling devices is the two-stage rotary cooler employed by the Atlas Portland Cement Company. It is, so far as the writer knows, the only cooling system which really cools the clinker to a handling temperature and does so quickly and economically.

The cooling system at the main Atlas plant was described by Stanger and Blount in 1901 as follows:

"The clinker drops from the burning cylinder into a second rotating cylinder, about 30 feet long and 3 feet in diameter, revolving about six times as fast as the burning cylinder. This is lined with fire-brick, and through it passes a current of air which goes to feed the flame of burning coal-dust. The greater part of the sensible heat in the clinker is thus saved and utilized. The clinker, still moderately hot, falls on to three crushing rolls contained in a housing and moistened by a spray of water. As shown in the figure a pair of kilns with their accompanying first cooling cylinders converge so as to deliver the clinker onto these rolls and from this point a single secondary cooling apparatus serves this pair of kilns. The object of the rolls is to crush large lumps of clinker which may have been formed by the aggregation of a number of small fragments adhering together when plastic in the burning cylinder. These lumps being built up of small pieces loosely stuck

together differ entirely from the tough hard masses formed in a fixed kiln fed with blocks or bricks of raw material, and are readily broken up to the size of a hazelnut. The warm moist clinker passes down a third rotating cylinder 60 feet long by 5 feet in diameter, lined with hard cast-iron plates provided with shelves so as to toss and tumble the pieces as they creep down. Air is drawn in through this cylinder by means of a chimney which also carries off the water vapor from the housing of the rolls. It is intended that the clinker shall emerge from the end of the last cooling cylinder, in a slightly moist condition,

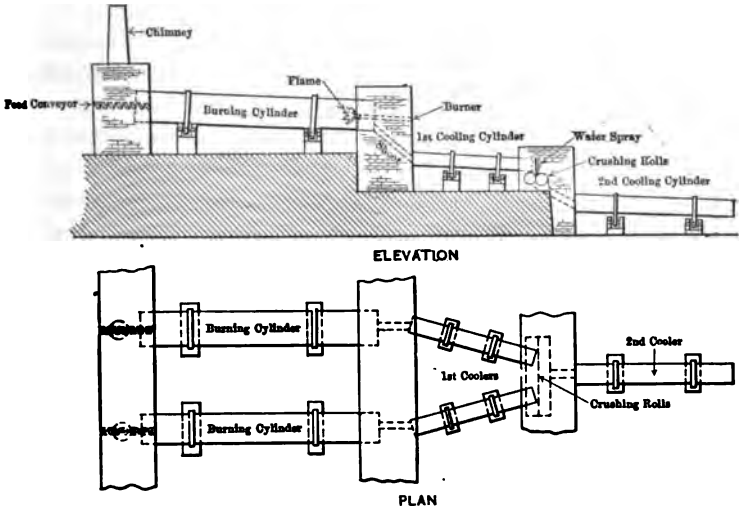


FIG. 121.—Atlas rotary two-stage coolers. (Engineering News.)

and to ensure this, regulation of the water at the rolls is supplemented by a small jet at the end of the last cooler."

This system is shown in Fig. 121, taken from the paper * below cited.

Clinker-grinding.

After cooling sufficiently to be workable, the clinker passes to the clinker-grinding department of the mill. The problem before this department is to reduce large quantities of an intensely hard and semi-vitrified material to finely ground cement at the lowest cost possible. This reduction is now usually accomplished in two or three stages.

* Stanger, W. H., and Blount, B. The rotary process of cement-manufacture. Proc. Inst. Civil Engineers, vol. 145, pp. 57–68. 1901. See especially p. 62 for coolers.

Somewhere in the process it is necessary to provide for the addition of a certain comparatively small percentage of gypsum or plaster, in order to bring the setting properties of the cement up to commercial requirements. Though this addition is commonly made *during* the grinding process, it will be discussed later in the chapter.

The power allowed and machinery installed for pulverizing the clinker at a Portland-cement plant using the dry process of manufacture are very closely the same as that required for pulverizing the raw materials for the same output. This may seem, at first sight, improbable, for Portland-cement clinker is much harder to grind than any possible combination of raw materials; but it must be remembered that for every barrel of cement produced about 600 lbs. of raw materials must be pulverized, while only a scant 400 lbs. of clinker will be treated, that the large crushers required for some raw materials can be dispensed with in crushing clinker, and that the raw side rarely runs full time. The raw material side and the clinker side of a dry-process Portland-cement plant are, therefore, usually almost or exactly duplicates.

The difficulty, and in consequence the expense, of grinding clinker will depend in large part on the chemical composition of the clinker and on the temperature at which it has been burned. The difficulty of grinding, for example, increases with the percentage of lime carried by the clinker, because of the higher burning which has been necessary, and a clinker containing 64 per cent of lime will be very noticeably more resistant to pulverizing than one carrying 62 per cent of lime. So far as regards burning, it may be said in general that the more thoroughly burned the clinker the more difficult it will be to grind, assuming that its chemical composition remains the same.

The tendency among engineers at present is to demand more finely ground cement. While this demand is doubtless justified by the results of comparative tests of finely and coarsely ground cements, it must be borne in mind that any increase in fineness of grinding means a decrease in the product per hour of the grinding-mills employed, and a consequent increase in the cost of cement. At some point in the process, therefore, the gain in strength due to fineness of grinding will be counterbalanced by the increased cost of manufacturing the more finely ground product.

The increase in the required fineness has been gradual but steady during recent years. Most specifications now require at least 90 per cent to pass a 100-mesh sieve; a number require 92 per cent; while a few important specifications require 95 per cent. Within a few years it is probable that almost all specifications will go as high as this.

Actual practice.—The following data relate to the machinery used on the clinker-grinding side of a number of American plants of modern construction, and will serve to give a good idea of current practice along that line:

Plant No. 1.
3 170′ kilns. 1600 barrels.
3 rotary coolers.
2 kominuters.
2 Smidth tube mills.

Plant No. 2.
3 140′ kilns (wet).
Dodge jaw-crusher.
4 Krupp ball mills.
5 Chalmers tube mills.

Plant No. 3.
5 kilns, 120 foot.
5 rotary coolers.
10 Fuller-Lehigh mills.

Plant No. 4.
2 kilns, 160 foot.
2 rotary coolers.
1 set crushing rolls.
4 Fuller mills.

Plant No. 5.
2 kilns, 140 foot.
Sturtevant crushers.
Griffin mills.

Plant No. 6.
24 kilns, 125-foot coolers.
18 Gates ball mills.
24 Gates tube mills.

Plant No. 7.
12 kilns, 120-foot.
12 Kent Maxecon mills.
15 tube mills.

Use and Effects of Gypsum or Plaster.

The high-limed clinker now produced in the rotary process is naturally very quick-setting. In order to retard its set sufficiently to pass commercial requirements, sulphate of lime, in the form of gypsum or plaster, is now universally employed. This substance, when added in quantities up to 2 to 3 per cent, retards the set of the cement proportionately, and also increases somewhat its tensile strength in short-time tests. In larger quantities, its retarding influence becomes less, and finally negative, while a decided weakening of the cement is noticeable.

The more theoretical part of the discussion, relating to the form in which the sulphate is applied, and the influence of various percentages of sulphate on the set and strength of the cement, will be first presented: after which the actual methods of application, with analyses of gypsums and plasters used in practice, will be discussed.

Form in which calcium sulphate is used.—The requisite calcium sulphate may be added to the cement in one of three forms: as crude gypsum, as calcined plaster, or as dead-burnt (anhydrous) plaster. For a full description of the manufacture and properties of these three products the reader is referred to Part I of this volume. In the present place their essential characters can be briefly stated as follows: Crude gypsum is a natural hydrous sulphate of lime, corresponding to the formula $CaSO_4+2H_2O$, and to the composition calcium sulphate 79.1 per cent, water 20.9 per cent. Calcined plaster, or plaster of Paris, is obtained by heating gypsum at temperatures of 350°–400° F., the result being that three-fourths of the combined water is driven off. The resulting plaster has the formula $CaSO_4+\frac{1}{2}H_2O$, corresponding to the composition calcium sulphate 93.8 per cent, water 6.2 per cent. If gypsum be calcined at temperatures much above 400° F., all of its combined water will be expelled, leaving dead-burnt or anhydrous plaster, which is simply $CaSO_4$.

Considerable discussion has been aroused over the question, which of these three forms of calcium sulphate is the more advantageous for use: but few satisfactory series of experiments are on record in regard to this point. A misleading statement often made is that plaster of Paris, because of its greater chemical activity, will naturally be much more effective than gypsum, weight for weight. The fallacy involved in this statement is revealed when it is considered that the calcium sulphate added to the cement has absolutely no effect until the mixture is gauged with water; and that this addition of water will naturally

reconvert the plaster immediately into the hydrous lime sulphate, gypsum. Any argument based on relative chemical activity, so-called, is therefore fallacious, but the higher SO_3 of plaster is effective.

The results of a few recorded experiments, on the comparative effects of the various forms of calcium sulphate, on the set and strength of the cement, will be given below; after which the conclusions which may be drawn from these experiments and from commercial conditions and actual practice will be summarized.

Nihoul and Dufossez, in the course of the experiments described on page 478, tested the comparative effect of calcium sulphate in four different forms—i.e., as crude gypsum, as calcined plaster, as anhydrous plaster and as chemically precipitated calcium sulphate. Their conclusions were: (1) that with the precipitated calcium sulphate and calcined plaster the retardation of set is proportional to the amount of sulphate added: and, (2) that with crude gypsum this is true only when less than 2 per cent of gypsum is employed, larger percentages causing acceleration rather than retardation of set.

Lewis has carried out a short series of experiments on the influence of calcium sulphate on the strength of the cement, applying the calcium sulphate in three different forms—gypsum, plaster of Paris, and anhydrous plaster. The results, given in the table below, are not decisive: but seem to show a somewhat greater regularity of effect when plaster of Paris or anhydrous plaster are used than when gypsum is employed.

TABLE 196.

EFFECT OF FORM OF SULPHATE USED. (LEWIS.)

Amount Added.	Tensile Strength, 7 Days Neat.			Tensile Strength, 7 Days, 3 : 1.		
	Anhydrous Sulphate.	Plaster of Paris.	Crude Gypsum.	Anhydrous Sulphate.	Plaster of Paris.	Crude Gypsum.
0 per cent.....	444	444	444	196	196	196
1½ " "	.....	589	.....	.....	212	
2 " "	647	651	673	.....	215	
3 " "	.....	729	541	.....	225	179
4 " "	663	524	533	148	165	194
5 " "	293	247	593	127	66	179
6 " "	.....	254	.....	.....	63	

To summarize the matter: The active retarding agent is the sulphur trioxide present in the gypsum or plaster. As anhydrous plaster and plaster of Paris both contain somewhat higher percentages of SO_3 than gypsum, they will exercise a proportionally greater retarding

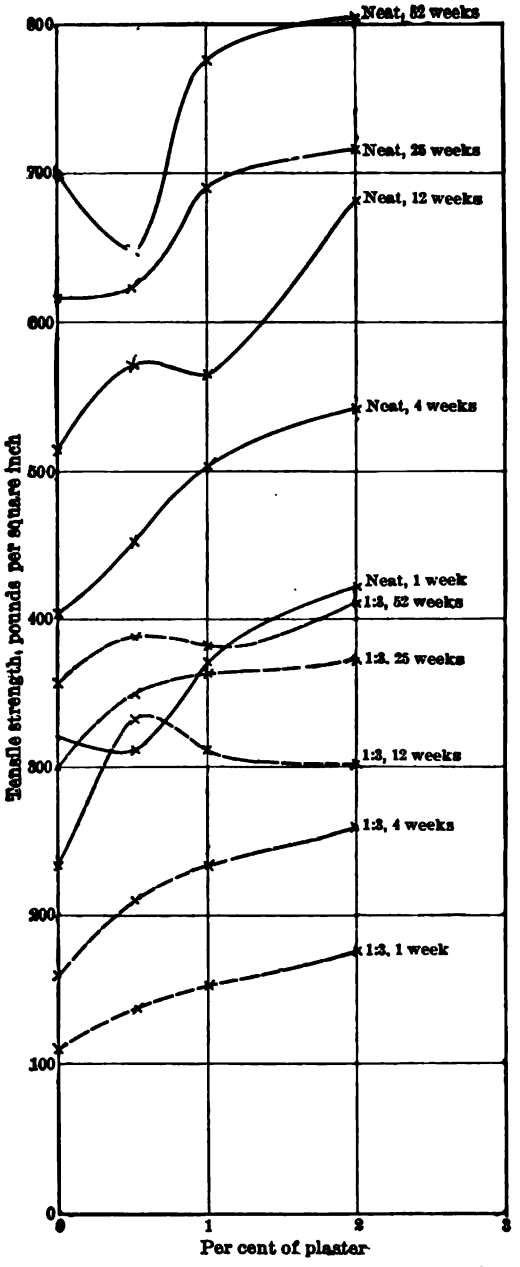


FIG. 122.—Effect of plaster on strength; different ages and compositions. (Dyckerhoff.)

effect, weight for weight, than will gypsum. But for ordinary practice this slight advantage is immensely counterbalanced by the fact that gypsum costs usually less than half as much as either of the plasters: and for ordinary practice, therefore, gypsum is the only form of cal-

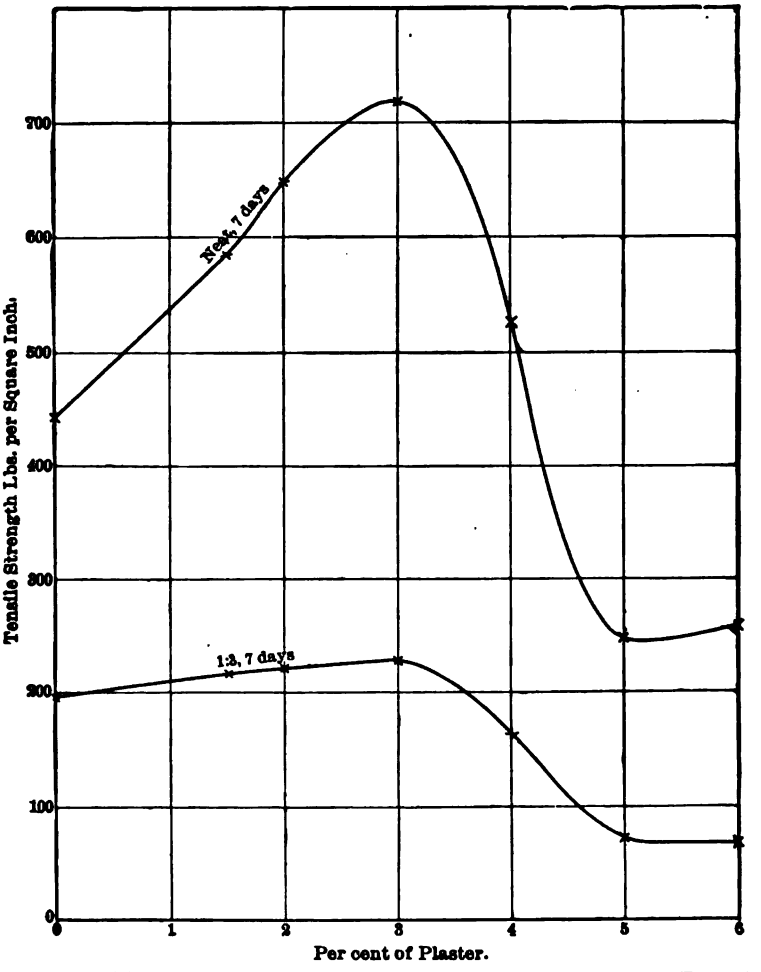


FIG. 123.—Effect of plaster on tensile strength of Portland cement. (Lewis.)

cium sulphate that can be considered available. In certain plants, however, where the sulphate is added *after* the cement has been ground, it is necessary to use plaster of Paris; because gypsum as bought is ground too coarsely to add to a finely pulverized cement.

Effect of calcium sulphate on set of cement.—Experiments on the effect of setting time of the addition of gypsum or plaster are fairly numerous. Unfortunately, such records mean very little, unless they are accompanied by sufficient data, as to the chemical composition, fineness, etc., of the cement; to enable some idea to be formed concerning the general type of cement tested. Experiments on low-limed cement can not be fairly compared with those carried out on high-limed cements; and cement made in stationary kilns behaves differently from the usual product of the rotary.

In the experiments * of Nihoul and Dufossez a commercial Portland cement of the following composition was used:

Silica (SiO_2)	22.80
Alumina (Al_2O_3)	7.79
Iron oxide (Fe_2O_3)	1.27
Lime (CaO)	65.80
Magnesia (MgO)	0.59
Carbon dioxide (CO_2)	1.36
Water	0.20

It is to be noted that this cement, though probably made in a stationary kiln, is very high-limed and correspondingly quick-setting. It can therefore be considered as closely similar to the average rotary clinker.

TABLE 197.

EFFECT OF ADDING VARIOUS PERCENTAGES OF CALCINED PLASTER. (NIHOUL AND DUFOSSEZ.)

Composition.	Initial Set. Hours.	Initial Set. Minutes.	Final Set. Hours.	Final Set. Minutes.
Pure cement	0	8	0	13
Cement with 1 per cent plaster	1	10	5	20
" " 1½ " " "	1	40	6	0
" " 2 " " "	2	7	6	32
" " 3 " " "	2	51	6	50
" " 4 " " "	3	0	7	10
" " 5 " " "	3	33	7	12

TABLE 198.

EFFECT OF CALCINED SULPHATE ON SET OF CEMENT. (DYCKERHOFF.)

Per Cent Plaster Added.	Setting-time, Hours.	Setting-time, Minutes.
0	0	20
1½	3	30
1	10	0
2	14	0

* Journ. Soc. Chem. Industry, vol. 21, pp. 859–860. 1902.

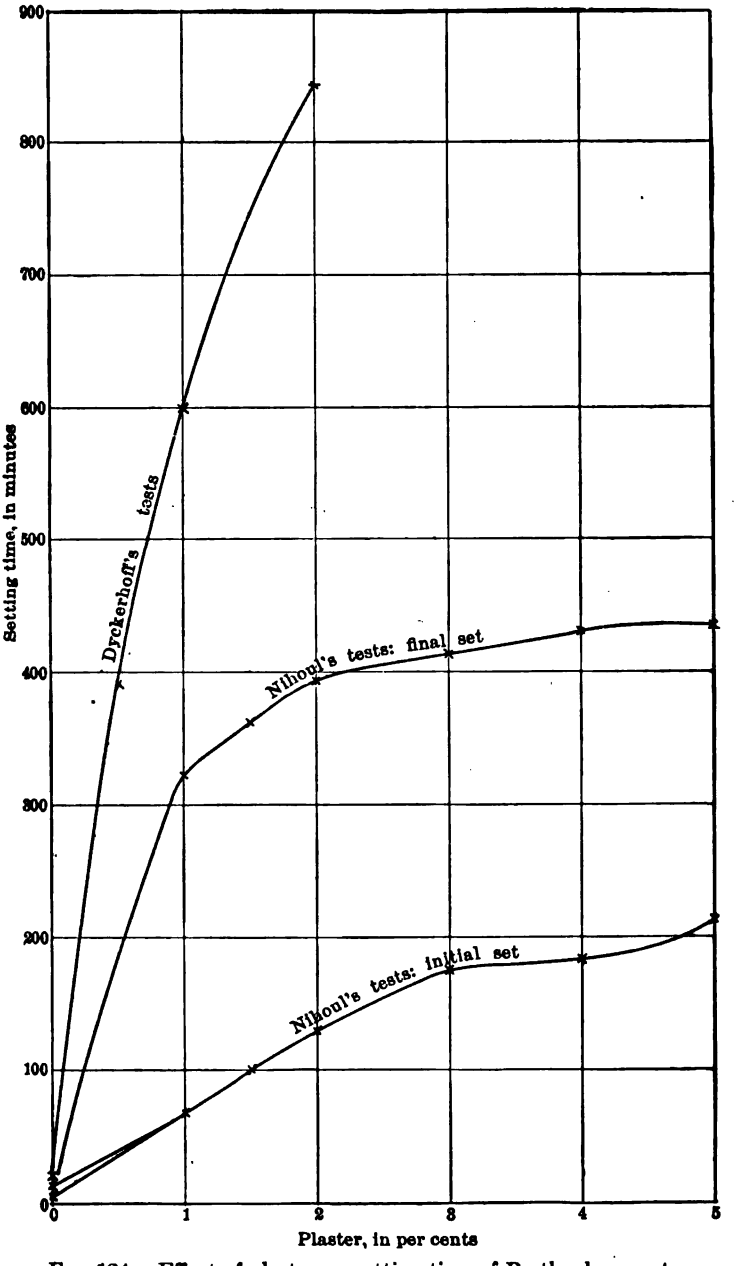


FIG. 124.—Effect of plaster on setting-time of Portland cement. (Dyckerhoff's tests; Nihoul's tests.)

Results obtained by Dyckerhoff * are given in the table above. It is unfortunate that no analysis of the cement experimented on is obtainable, in view of the remarkably great retardation effected by very small percentages of sulphate.

A very unusual set of results, obtained in experiments, by Messrs. Kniskern and Gass, has recently been published † by Prof. R. C. Carpenter. Clinker was procured from a cement-plant in unground form and ground in the laboratory, being mixed with various percentages of gypsum. The results are as follows:

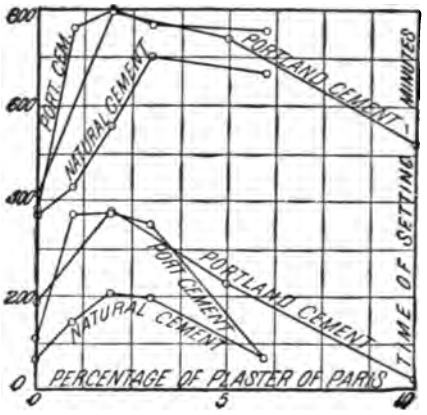


FIG. 125.‡—Effect of plaster on setting-time. (Sabin.)

TABLE 199.

EFFECT OF GYPSUM ON SETTING-TIME. (KNISKERN AND GASS.)

Per Cent Gypsum.	Initial Set, Minutes.	Final Set, Minutes.	Per Cent Gypsum.	Initial Set, Minutes.	Final Set, Minutes.
0	2	52	4	28	45
½	6	87	4½	22	40
1½	80	157	5	27	59
2	24	114	5½	20	78
2½	29	79	6	19	37
3	30	69	6½	22	40
3½	27	72	7	18	59

These results are shown diagrammatically in Fig. 126 and comparison of this curve with those of Figs. 124 and 125 will show their unique

* Proc. Inst. Civ. Engrs., vol. 62, p. 156. 1880.

† Engineering News, vol. 53, pp. 13–14. Jan. 5, 1905.

‡ From Johnson's "Materials of Construction," p. 187.

character. The maximum effect was obtained with 1½ per cent of gypsum, and a rapid decrease in effect was shown when 2 per cent or

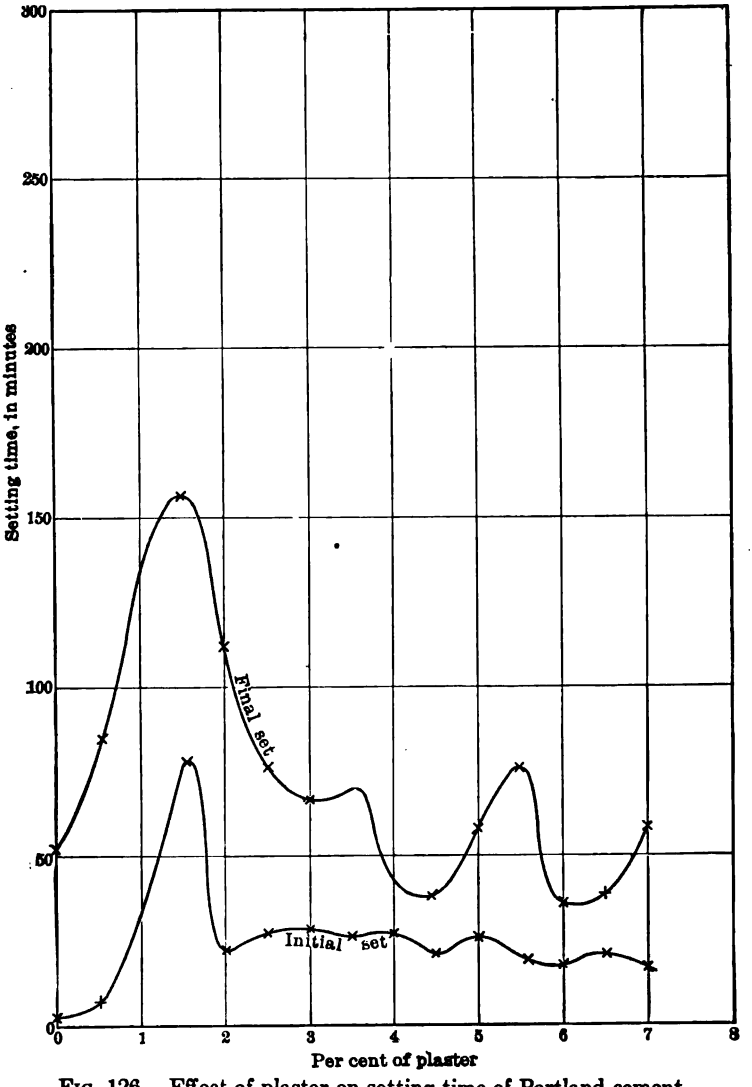


FIG. 126.—Effect of plaster on setting-time of Portland cement. Kniskern and Gass, 1905.

more was used. Unfortunately no analysis is given of the cement experimented on, so that we cannot judge whether or not there is any reason for these curious results.

Effect of calcium sulphate on strength of cement.—In addition to retarding the set of the cement, gypsum or plaster exerts an interesting influence on its strength and, in some cases, its soundness.

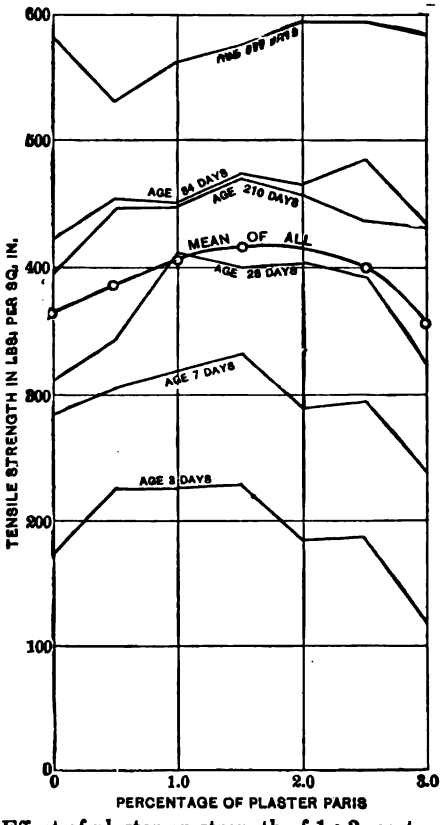


FIG. 127.*—Effect of plaster on strength of 1 : 3 mortar. (Tetmajer.)

TABLE 200.

EFFECT OF CALCIUM SULPHATE ON STRENGTH OF CEMENT. (DYCKERHOFF.)

Percentage Gypsum.	Time of Set.		Neat Cement.					1 Cement : 3 Sand.				
	Hrs.	Min.	1 Week.	4 Wks.	12 Wks.	25 Wks.	52 Wks.	1 Week.	4 Wks.	12 Wks.	26 Wks.	52 Wks.
0	0	20	323	405	518	620	700	115	168	238	302	360
½	3	30	315	456	572	623	650	142	212	339	353	390
1	10	0	375	508	568	695	780	159	238	311	368	384
2	14	0	425	543	688	718	805	180	263	305	375	410

* From Johnson's "Materials of Construction," p. 187.

TABLE 201.

EFFECT OF CALCIUM SULPHATE ON STRENGTH OF CEMENT. (GRANT.)

Per Cent SO_3 Added.	Neat Cement.				1 Cement : 1 Sand.			
	7 Days.	30 Days.	60 Days.	90 Days.	7 Days.	30 Days.	60 Days.	90 Days.
0	313	500	536	605.4	106.8	159.2	188.4	266.8
½	305	503	567	618.0	129.2	226.6	259.6	255.2

TABLE 202.

EFFECT OF TREATMENT WITH ANHYDROUS CALCIUM SULPHATE. (LEWIS.)

Per Cent Sulphate Added.	Tensile Strength.	
	7 Days: Neat.	7 Days: 3 : 1.
0	444 lbs.	196 lbs.
2	647 "	
4	663 "	148 "
5	293 "	127 "

TABLE 203.

EFFECT OF TREATMENT WITH CRUDE GYPSUM. (LEWIS.)

Per Cent Gypsum Added.	Tensile Strength.	
	7 Days: Neat.	7 Days: 3 : 1.
0	444 lbs.	196 lbs.
2	673 "	
3	541 "	179 "
4	533 "	194 "
5	593 "	179 "

TABLE 204.

EFFECT OF TREATMENT WITH PLASTER OF PARIS. (LEWIS.)

Per Cent Plaster Added.	Tensile Strength.	
	7 Days: Neat.	7 Days: 3 : 1.
0	444 lbs.	196 lbs.
1½	589 "	212 "
2	651 "	215 "
3	729 "	225 "
4	524 "	165 "
5	247 "	66 "
6	254 "	63 "

Methods of using gypsum.—From what has been said on preceding pages, it is evident that in Portland-cement manufacture either gypsum or burned plaster may be used to retard the set of the cement. As a matter of fact, gypsum is the form almost universally employed in the United States. This is merely a question of cost. It is true that to secure the same amount of retardation of set it will be necessary to add a little more of gypsum than if burned plaster were used; but, on the other hand, gypsum is much cheaper than burned plaster.

The addition of the gypsum to the clinker is usually made before it has passed into the ball mill, kominuter, or whatever mill is in use for preliminary grinding. Adding it at this point secures much more thorough mixing and pulverizing than if the mixture were made later in the process. At some of the few plants which use plaster instead of gypsum, the finely ground plaster is not added until the clinker has received its final grinding and is ready for storage or packing.

Analyses of gypsum used.—The following analyses will serve to illustrate the composition of the crude gypsum and of the calcined plaster used at different American Portland-cement plants.

TABLE 205.

ANALYSES OF GYPSUM USED IN CEMENT-PLANTS.

Silica (SiO_2)	0.32	0.86	5.10	7.26	n. d.
Alumina (Al_2O_3)	0.87	0.36			n. d.
Iron oxide (Fe_2O_3)					n. d.
Lime (CaO)	31.94	30.84	n. d.	n. d.	35.8
Magnesia (MgO)	0.52				
Sulphur trioxide (SO_3)	44.93	43.60	40.20	43.20	43.6
Carbon dioxide (CO_2)					
Water	20.95	21.68	n. d.	n. d.	20.3

TABLE 206.

ANALYSES OF CALCINED PLASTER USED AT CEMENT-PLANTS.

Silica (SiO_2)	0.83	1.10	n. d.
Alumina (Al_2O_3)	0.46	0.32	n. d.
Iron oxide (Fe_2O_3)			
Lime (CaO)	38.58	37.87	37.26
Magnesia (MgO)	0.50	0.73	1.11
Sulphur trioxide (SO_2)	54.12	53.26	50.50
Carbon dioxide (CO_2)	n. d.	n. d.	3.40
Water	5.61	6.32	5.50

Effect of various salts on set of cement.—Experiments have been made on the use of various other salts—sulphates, phosphates, chlorides, etc.—by different chemists. Few of the results thus obtained are of any

practical importance, for most of the salts experimented with are too costly for use.

TABLE 207.

EFFECT OF VARIOUS SALTS ON SET OF CEMENT. (NIHOUL AND DUFOSSEZ.)

	Initial Set. Hrs.	Min.	Final Set. Hrs.	Min.
Pure cement	0	8	0	13
Cement with 2 per cent calcium sulphate	2	7	6	32
" " 2 " " strontium sulphate	0	3	0	5
" " 2 " " barium sulphate	0	3	0	4
" " 2 " " calcium phosphate	0	8	0	18
" " 2 " " " aluminate	0	1	0	3
" " 2 " " precipitated silica	0	5	0	6½

Recent experiments on the use of solid chloride of lime as a retarder have been published by Carpenter. These were carried out by the same experimenters, and probably on the same cement which, when treated with gypsum, gave the erratic results noted on page 480. Carpenter summarizes * these experiments as follows:

" Messrs. Kniskern and Gass, in the Sibley Laboratory, ground different percentages of chloride of calcium ($CaCl_2$) with cement clinker and afterwards made pats, using in each case simply enough water to give the material its normal consistency for this purpose. Their results show that the chloride of calcium had great effect in retarding the time of setting and exerted the greatest effect when about 0.5 per cent by weight of the chloride of calcium was employed. On account of the water required, 1 per cent of the chloride of calcium would correspond approximately to gauging with a solution of 30 grams per liter in the previous experiments quoted.

$CaCl_2$ GROUND DRY WITH THE CLINKER.

Per Cent of $CaCl_2$.	Per Cent of Water.	Initial Set, Minutes.	Final Set, Minutes.
0.0	29.8	2	52
0.5	34.1	115	274
1.0	29.8	160	272
1.5	26.4	167	234
2.0	25.4	127	212
2.5	26.4	103	180
3.0	26.4	45	182
3.5	26.4	97	185
4.5	28.6	63	150
5.0	29.8	73	160
5.5	29.8	76	84
6.0	29.8	68	145

* Engineering News, vol. 53, pp. 13-14. Jan. 5, 1905.

"The experiments quoted indicate that chloride of calcium added in small percentages either to the ground clinker as a powder or mixed with the water for gauging has an important effect in extending the time of setting of Portland cement, and so far as the investigations which are accessible show it does not have any detrimental effect on the permanent strength and hardness.

"Chloride of calcium is a deliquescent material which rapidly absorbs moisture, and it is possible that if ground dry with the Portland-cement clinker, even to the amount of ½ per cent, it would cause the material to gather dampness and thus have a bad effect. The chloride of calcium solution can be added readily by adding it to the water used in gauging, since it dissolves with extreme rapidity. The experiments indicate that the set can be controlled by using less than ½ per cent, which would be something less than 2 lbs. to the barrel of Portland cement. Investigations are still necessary for determining whether the effect of chloride of calcium added to the cement before grinding is permanent in its effects, and whether if ground with the cement clinker it would avert any detrimental effect."

List of references on use of calcium sulphate, chloride, etc.

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Storage, Packing, and Market.

Necessity for storage.—A twofold necessity exists for large storage space at a modern cement-plant. The cement will in many cases be improved by storage, particularly if it can be so stored that air will gain access to the mass. Aeration in the storage building is, however, rarely possible; and in consequence the tendency now is in the direction of aerating or slaking the clinker *before* grinding. The main reason for storage still remains prominent. It is caused by the fact that while the average mill runs twelve months in a year, the cement-selling period, in most of the United States, is practically confined to six months or even less. This of course necessitates very extensive storage facilities—enough to hold at least three months' output of the mill, and preferably to hold six months' production. This means that for each kiln in a dry-process plant, storage space for at least 20,000 barrels should be provided. As Portland cement dumped from a conveyor will pile up so as to weigh about 90 to 100 lbs. per cubic foot, the storage space above stated (20,000 barrels) would be equivalent to about 80,000 cubic feet for each kiln in the plant. This is the minimum of space that can be given with safety, and an allowance of 150,000 cubic feet per kiln would be much better for the average plant in the Middle or Eastern States. In the South and West conditions are different, and much less storage space is required.

The question as to whether this storage is to be mainly for unground clinker or for finished cement is largely a question of climate. Mills located in wet regions will be forced to carry essentially all their surplus in the form of clinker, because of the deterioration otherwise. For mills located in drier regions it will be possible to carry larger proportionate amounts of finished cement. For other reasons clinker storage has advantages; so that the tendency everywhere seems to be in the direction of providing more and more space and facilities for the storage of unground clinker.

Designs of storage buildings and bins.—In Figs. 128, 129, 130, and 131 are given plans of several recently erected storage buildings and bins. Those shown in Fig. 128 are concrete-steel bins erected for the Portland-cement plant of the Illinois Steel Co. for clinker storage.

The stock-house and bins shown in Figs. 129, 130, and 131 are those of the Hudson Portland Cement Co. In a description of that plant accompanying these figures * the following data are given: "The stock-house is a structure 410 feet long and 105 feet wide, having as foundations a series of concrete walls founded on piles. It contains three groups of twenty bins each. The bins are of wood, their walls being laid up

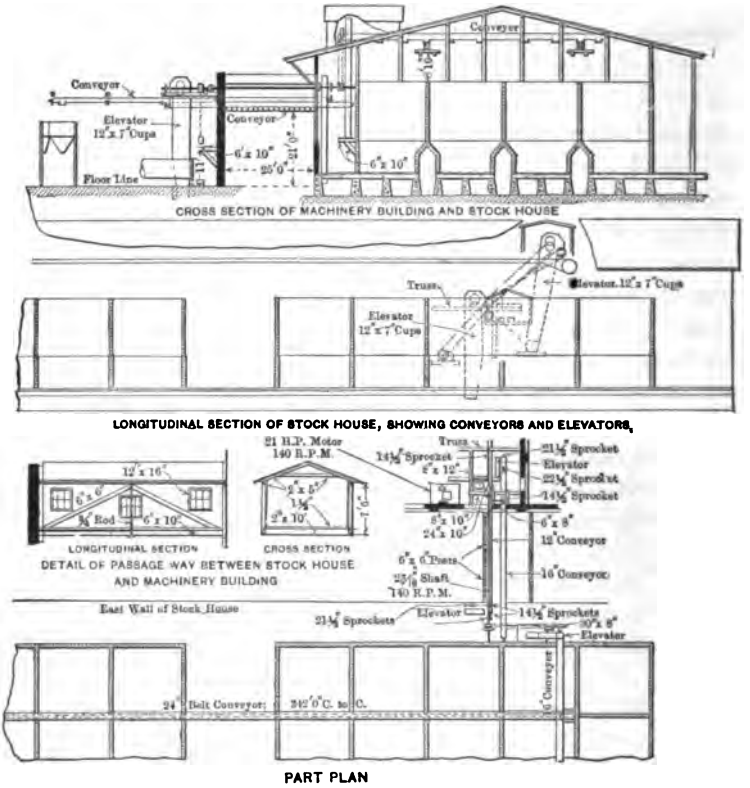

FIG. 129.—Plan and sections of stock-house, Hudson Portland Cement Co., showing conveying machinery. (Engineering News.)

solid of $2'' \times 10''$ and $2'' \times 8''$ plank laid flat and spiked together. The total capacity of the bins is 200,000 barrels of cement. Cement is conveyed to the stock-house from the mill by means of conveyor 26, which discharges into the boot of elevator *O*. This elevator discharges into the transverse screw conveyor 27, which spouts onto two belt conveyors running lengthwise of the building over the bins. From these belts the cement can be deflected into any one of the 60 bins."

* Engineering News.

Testing at the mill.—The contents of each bin should be sampled as soon as it is filled, and the usual physical tests made on these samples, supplemented by analysis if need be. If the cement is weak or unsound, it is far better in every way to detect it at the mill than to run the risk of having it rejected at the work.

Of recent years it has become the fashion, in specifications for cement for important work, to require that the purchaser should be represented

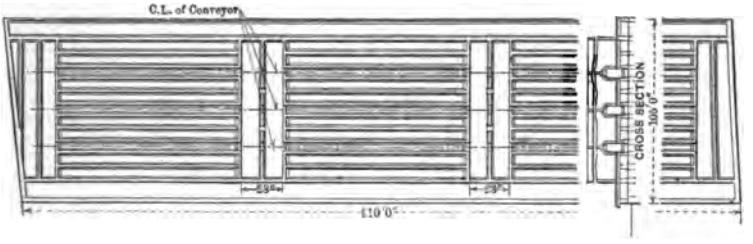

FIG. 130.—Foundation plan of cement stock-house, Hudson Portland Cement Co.

at the cement-mill by an inspector during the manufacture and shipment of the cement covered by the specifications. This practice, if taken up in a proper spirit by both sides, will prevent many difficulties and misunderstandings, so that it has a good moral effect.

Farther than that the gains are not so obvious. Mill inspection can protect the purchaser against adulteration after burning, but as it happens that is not a common vice at American plants, though still

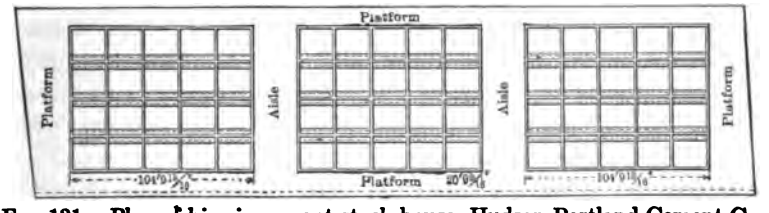

FIG. 131.—Plan of bins in cement stock-house, Hudson Portland Cement Co.

existing in Europe. It can not be carried out so as to insure the proper conduct of earlier operations, however. In any case it involves some extra work for the mill and it should be paid for separately.

Packing and packing weights.—Cement packing is usually carried out mechanically, with relatively little differences between the different devices employed. Packing house costs will commonly range between two and five cents per barrel, on the 1900–1915 price level.

According to the recently issued specifications of the American

TABLE

CAPACITY OF PORTLAND-CEMENT BARRELS AND

Number Barrels Tested; Results Averaged.	Brand.	Height between Heads, Feet.	Average.		Capacity Barrel between Heads, Cu. Ft.	Depression, Cement below Head, Feet.	Volume of Depression, Cu. Ft.
			Diameter of Barrel, Feet.	Horizontal Area, Sq. Ft.			
6	Giant.....	2.19	1.430	1.605	3.495	0.12	0.171
6	Alsen.....	2.08	1.403	1.546	3.219	0.04	0.059
3	Saylor's.....	2.07	1.412	1.571	3.249	0.07	0.096
5	Dyckerhoff.....	2.01	1.407	1.554	3.123	0.07	0.093
1	Fiske Lion *.....	2.13	1.38	1.496	3.186	0.03	0.039
5	Atlas.....	2.12	1.437	1.622	3.446	0.17	0.235
5	Aalborg †.....	2.01	1.455	1.662	3.327	0.10	0.148
	Final Averages.....	2.09	1.418	1.579	3.292	0.09	0.120

* Hanover. † Denmark. ‡ Partial averages. To be compared only with

Society for Testing Materials, quoted later, Portland cement should be packed in bags of 94 lbs. net weight, four of which make a barrel of 376 lbs. net. Several other important specifications require a barrel of 170 kg. net. In ordinary calculations it is often assumed for convenience that a barrel of Portland cement weighs 400 lbs. gross or 380 lbs. net. The following table (209), published some years ago by Mr. Sanford Thompson,* gives the results of a series of actual tests on the weight, size, etc., of cement barrels:

At present a very large proportion of American cement is marketed in sacks or bags, packing in wood being almost entirely confined to cement intended for export or coastwise shipment. Foreign cement, of course, reaches the American market in barrels, but imported cements are becoming of less consequence each year.

When cement is packed in wood, the barrels are usually charged for at a rate sufficient to give a slight profit to the packing department of the mill. Bags and sacks are also charged extra, with a rebate for returned bags. In figuring the cost of cement manufacture it is therefore unnecessary to include the actual cost of the packages, but the labor and power used in the packing-house must be figured in.

* Thompson, Sanford E. Weights of Portland cement and capacity of cement barrels. Engineering News, Oct. 4, 1900. For a more detailed discussion of the subject, reference should be made to Taylor and Thompson's "Concrete, Plain and Reinforced," 1905, pp. 216 et seq.

208.

WEIGHT OF CONTENTS. (HOWARD A. CARSON.)

Volume of Cement per Barrel.			Net Weight of Cement per Barrel at Dumping.		Weight per Cubic Foot.				Weight of Barrel, Pounds.
Packed, Cu. Ft.	Loose, Cu. Ft.	Shaken, § Cu. Ft.	Before, Pounds.	After, Pounds.	Packed, Pounds.	Loose, Pounds.	Shaken, Pounds.	Sifted, Pounds.	
3.347	4.173	.....	381.0	.....	113.81	91.38	.....	.....	29.0
3.161	4.192	.....	374.2	.....	118.45	89.20	.....	.....	24.3
3.152	4.052	.....	387.0	.....	122.75	94.24	.....	.....	22.7
3.031	3.989	3.522	373.2	371.4	123.16	93.18	105.54	.....	25.6
3.147	4.270	3.695	378.0	378.0	120.11	88.52	102.29	.....	22
3.211	3.754	3.432	377.4	376.9	117.54	100.49	109.45	90.6	21.1
3.206	4.058	3.598	370.7	370.2	115.71	91.40	102.94	80.3	23.3
3.179	4.070	3.562‡	377.4	374.1‡	118.79	92.63	105.06‡	85.4‡	24.0

like brands. § Box rocked over bar. *Note.*—Paper weighs about 1 lb.

Packing weights of different countries.—The normal or legal weights of the cement packages—bags and barrels—of the chief-producing countries may be summarized as follows:

TABLE 209.

PACKING WEIGHTS OF CEMENT IN CHIEF COUNTRIES.

	Bags, kg. = Bags, Lbs.	Barrels, kg. = Barrels, Lbs.
United States	42.64 = 94	171.55 = 376
Australia	56.70 = 125	170.10 = 375
Canada	39.69 = 87½	158.76 = 350
Great Britain	Variable	Variable;
France	50	170
Denmark	85	170
Belgium	85	170
Switzerland	50 gross	200 gross
Austria	50 gross	200 gross
Germany	85 net	170 net

From this table it will be seen that there is a certain amount of uniformity growing up in this matter, in spite of the appearance of diversity due to different ways of quoting the weights and of dividing the barrel. For example, the United States, Australia, Germany, Denmark and Belgium pack a barrel of close to 170 kg. or 375 lbs. net; though they divide this unit into from two to four sacks, which, of course, range from 42½ to 85 kg. each.

As against this group, there are Canada and England, packing the old export barrels of 3½ bushels = 350 lbs. net. There are Switzerland and Austria using a sack of 50 kg. *gross* and a barrel of 200 kg. *gross*. And, highest normal unit of all, France packs sacks of 50 and 100 kg. *net* respectively.

It is worth noting that none of these units (except those of France) make an aliquot part of a short ton, a long ton or a metric ton.

CHAPTER XXXV.

COSTS, PRICES AND PRODUCTION.

In any discussion of the costs of Portland cement manufacture, and of the past and future trend of prices, it will be obviously useless to take into consideration the exaggerated figures of the past five years in respect to either factor. These prices are transitory, being expressed in a very badly depreciated currency; as sanity slowly returns to individuals and to governments we may fairly expect to see a return toward our older bases of comparison. Yet even here we can not expect too much in the near future; we will in all probability not get down again to the cost and price level of 1900, for example, for twenty years. Many of us in fact do not believe that we can ever return to the low levels established in 1896–1898 at any time, in such industries as have any extensive use for coal, oil and steel. The reasons for this doubt arise from consideration of certain conditions which are beginning to affect the world's supplies of these great basal commodities; the facts and the conclusions drawn from them have been elsewhere* discussed in the detail which their importance demands. Here we need only point out that these uncertainties as to the future course of costs and prices do exist, and that they will affect very seriously the trend of affairs in industries using these particular commodities in any extensive way. The Portland cement industry happens to be one of these.

In order to make use of data accumulated by various plants over a long series of years, we must therefore take into account the average course of commodity prices. Reference to pages 7–9 and to Fig. 132 will serve to explain both the necessity for doing this, and the uses to which the data so treated may be put. In all of the discussion in the present chapter it is to be understood that the data are based on the 1910–1915 price-level as being equal to 100. These six years, which showed very little fluctuation in the average level of commodity prices, are convenient for our present purpose; and data presented on that basis will be of permanent value and use. They are convertible into figures for any specific year by simple multiplication of the 1910–1915 data by

* Coal, Iron and War; a study in Industrialism past and future. New York, 1920; London, 1921.

the index number for the particular year in question, as given in Table 2, page 7. For example, to convert a cost or a price figure quoted on the 1910 basis to its 1918 value, we would multiply by 1.96; to convert it to the high figure of our post-war period, culminating in 1920, we would multiply the 1910–1915 figure by 2.44. For the years immediately in prospect, we may safely assume that in the course of five years—say by 1926—we will reach an average level of 150; and that by 1936 we may be down again to 120 or thereabouts.

In order to give a concrete example of how the war-time fluctuations in currency values affected cement costs, the following data are serviceable. They cover the experience, during the years 1913 to 1921 inclusive, of a very large group of American mills, representing in total about one-quarter of the Portland cement output of the United States. The actual costs of these mills are later discussed; hence we are interested in the yearly fluctuations, and on that account I have reduced all the costs to a basis of 100 for the year 1915.

TABLE 210.

FLUCTUATIONS IN CEMENT COSTS, 1913–1921.

	1913.	1914.	1915.	1916.	1917.	1918.	1919.	1920.	1921.
Average expenses per barrel	105	105	100	117	162	209	211	261	233

It will be seen that the costs of cement manufacture varied closely enough with the changes in average commodity costs as tabulated on page 7.

Costs of Portland Cement Manufacture.

Elements of cost.—The factors which fix the cost of cement manufacture at any given plant, or in the industry taken as a whole, may be summarized and grouped as follows:

A. Cost of cement materials delivered at mill.

1. Quarry labor.
2. Quarry supplies.
3. Transportation to mill.

B. Mill costs proper.

4. Mill labor.
5. Coal for fuel and power.
6. Gypsum, oil, supplies.

7. Mill superintendence and laboratory.
8. Mill repairs.

C. Administrative and selling costs.

9. Salaries and expenses sales department.
10. Salaries and expenses general offices.
11. Insurance and taxes.

D. Depreciation allowances for quarry and mill.

If the costs included under *A*, *B* and *C*, are just covered by the price of the cement, the mill can run and be kept in condition; but taken over any long period there would be no profits of any sort, and the capital used would not have paid interest. Of course no sane person would intentionally go into a business of that sort, but unfortunately a good many companies have made a record just like that, or worse. On the other hand it is obvious that the bulk of the output must necessarily be sold at a profit, or the industry would have died out long ago.

It might be added, also that if the average selling price merely amounts to $A+B+C$, though the mill would just pay its way, it might not remain in the hands of its original owners. For if the original capital had been raised in part by means of a bond issue, the interest charges or sinking fund requirements on these bonds could not be met under the condition assumed. That contingency also has arrived to a number of American plants during the past twenty years. For further consideration of the financial aspects of such enterprises, the reader must be referred to a publication * which represented about the first attempt to deal sanely with promotion possibilities, and which contains matter still serviceable in that connection.

Finally, it may be noted that unless the items *D* are also covered by the selling price of the cement, the company will at the end of a certain period find itself without any raw materials left on its quarry lands, and with a mill that has gradually gone to pieces from old age. This too has happened to a few American plants; and will probably happen to others in the course of time.

The four groups of cost-factors above noted will be discussed in turn.

A. **Cost of cement materials at mill.**—The methods and actual excavation cost of cement materials is discussed, with very recent and entirely reliable figures for cost of a number of actual operations, on pages 352 to 355. Here it will be only necessary to add to these figures the two elements which were purposely omitted in the earlier discussion.

* The Portland Cement Industry from a Financial Standpoint, New York, 1908.

Reference is made, of course, to transportation charges and to quarry depreciation.

As regards the first point, there is a very wide variety as between different plants. Most of the older plants in the East and Middle West are located at or very close to, their quarries, and in these cases transportation of raw materials to the mill may be a very small item of cost. But in a surprisingly large number of plants, and these not by any means the smaller ones, there is a more or less heavy rail charge to be added to the quarry cost on one or both of the raw materials. And there are also a few plants—and here again some very large ones—which buy one or more of the raw materials. It is obvious that these matters can not be discussed in detail without practically designating the plants under discussion, so I am merely noting these facts here, in order to assure the reader that they are allowed for in the data presented later.

In addition to actual working and transport costs the raw materials should carry certain other charges and allowances. These must cover the depreciation or replacement charges of all sorts—on quarry equipment, on the first cost of opening and preparing the operation, and on the raw material supply itself. It will be most convenient to consider all of these together under heading *D*, depreciation allowances.

Records of a number of important mills, ranging in size from medium to very large, and showing a wide range in types of raw materials used, gave costs (per barrel of cement) for raw material delivered at mill that ranged from 5.8 cents up to 21.19 cents. The three highest costs were due in each case, not to high quarry costs but to high freight rates from quarry to mill. The arithmetical average for the entire lot would be 13.28 cents per barrel cement. A weighted average would be somewhat higher, since some of the very largest of the mills had the highest raw material costs. But for the American industry as a whole the unweighted average is probably fair enough, on the 1910–1915 price level.

B. **Mill costs proper.**—The mill costs proper, as here defined, include all the charges for drying, grinding and burning the raw materials, for grinding and packing the cement, and for the necessary chemical and mechanical supervision of these operations. They should also include depreciation charges against the mill, but for convenience these allowances will be taken up, like quarry depreciation, under *D*.

Mill costs are made up of a very large number of items, which can be grouped either by department or by character of cost itself. The former is convenient from one point of view, and has been considered earlier in this volume where fuel and power costs are discussed by depart-

ment. For our present purposes it will be far more useful to group them in the other way, according to the character of the cost item itself.

Looked at in this manner we can pick out immediately two large items—those relating to labor, and those relating to fuel and power. The labor and coal items, taken together, make up commonly three-quarters of all the mill costs. The balance is made up by certain supplies—i.e., gypsum, oil, repair parts, etc.—and by the cost of superintendence, mill office and laboratory.

The ordinary range in distribution of the different items is brought out well enough by the tabulation following, covering long-time results at five mills, in percentages of the total mill costs.

TABLE 211.

MILL COSTS.

Item.	No. 1.	No. 2.	No. 3.	No. 4.	No. 5.	Average.
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Labor	26	43	30	28	29	31
Kiln coal	23	18	16	27	15	20
Power coal, etc	26	24	23	26	23	24½
Supplies	22	13	25	15	26	20
Office, etc	3	2	6	4	7	4½
	100	100	100	100	100	100

Of the costs above tabulated, one has been heretofore published by another engineer; the remainder are from my own records. It might be noted that two exceptional mills are included, one as regards high labor cost, another as regards power plant. But these exceptions, being in opposite directions, are smoothed out by the arithmetical average given in the last column.

As to total costs per barrel, records covering an important group of mills show (always on the 1910–1915 price level, be it understood) total costs that may be summarized as follows: The lowest mill cost for a year or more was 36 cents per barrel; the highest was 70½ cents; the arithmetical average for the group, covering perhaps a quarter or more of the total American cement output during that period, was 53 cents. This, however, happens to be entirely too high, because the very large mills included had by far the lowest mill costs, while two very exceptional small mills have too much effect on the merely arithmetical average. Weighted by barrels of output, the average would be reduced to a total mill cost of about 42 cents per barrel.

Total cost on cars.—The sum of the two cost-groups so far considered (*A* and *B*) is of course the actual net cost of cement on cars; disregarding depreciation, administrative expenses, sales and advertising. This sum, which is of course not a proper basis for fixing prices, ranged for an important number of mills, during periods of a year or more—still on the 1910–1915 price level—from 54.24 cents up to 91.70 cents per barrel, f.o.b. cars at mill. The arithmetical average for the mills considered is 64.55 cents. But here again the large mills had the lowest costs, so that a properly weighted average would fall between 55 and 60 cents per barrel.

The relation between the main items in the cost f.o.b. cars and the fluctuation of both these items and the total, over a period of recent years, is well shown in the table below, which gives the actual data for three companies of various sizes none of which were included in the group above noted, for the years 1913–1921 inclusive. It may be noted that the order in which these three companies are arranged in Table 212 following has purposely no relation to the size of the company:

TABLE 212.

QUARRY AND MILL COSTS OF CEMENT, 1913–1921.

	1913.	1914.	1915.	1916.	1917.	1918.	1919.	1920.	1921.
Company A.									
Coal.....	20.06	19.65	18.24	19.23	27.18	34.00	32.86	44.53	34.18
Material.....	12.72	12.97	12.23	13.49	16.54	22.70	23.75	26.57	26.35
Labor.....	24.27	26.10	23.86	26.95	32.89	40.56	48.16	54.46	40.38
	57.05	58.72	54.33	59.67	76.61	97.26	104.77	127.56	100.91
Company B.									
Coal.....	22.10	23.20	21.70	25.80	48.67	36.58	33.39	66.83	48.80
Material.....	8.58	8.83	10.64	9.02	12.32	16.59	19.98	28.92	25.05
Labor.....	16.70	19.25	16.17	16.82	23.04	28.18	25.06	33.73	24.19
Repairs.....	4.78	4.82	3.99	5.11	8.07	10.24	11.39	17.49	15.78
	52.16	56.10	52.50	56.75	92.10	91.59	89.82	146.97	113.82
Company C.									
Coal.....	21.52	19.66	18.26	23.10	41.84	45.71	37.14	58.41	45.54
Material.....	10.06	12.10	11.30	7.84	11.56	19.37	21.00	24.87	30.53
Labor.....	14.84	16.59	16.14	20.44	26.35	35.72	35.53	45.61	31.50
	46.42	48.35	45.70	51.38	79.75	100.80	94.67	128.89	107.57

C. **Administrative and selling costs.**—Heretofore we have been dealing with items of cost which have some necessary and reasonable relation to the work done, but in *C* and *D* we reach cost items of another

class; and in consequence they show a far wider variation per barrel of output than do any of the other cost items.

The administrative and selling costs may range from 5 cents a barrel to 25 cents and perhaps more, though it must be admitted that such extremes are exceptional. The wide range is due, not to variation in salaries and general expenses, but to differences in selling methods and agreements. Other overhead charges also vary widely.

As typical of the wide range in these overhead items, from mill to mill and from year to year, the actual costs of such items totaled as follows for four American companies for the years 1913 to 1921 inclusive. The totals cover, in each case, general and administrative expenses, selling and shipping costs, advertising, taxes, insurance, etc. All are quoted in cents per barrel.

TABLE 213.

OVERHEAD COSTS OF CEMENT COMPANIES, 1913–1921.

Year.	Company D.	Company E.	Company F.	Company G.
1913	15.70 cts.	12.38 cts.	18.08 cts.	13.39 cts.
1914	17.13	14.90	16.11	16.77
1915	17.43	13.92	12.85	14.84
1916	12.94	17.71	23.93	14.59
1917	21.74	23.85	15.51	.....
1918	27.89	32.33	43.37	31.94
1919	28.58	33.32	45.83	34.93
1920	25.64	31.84	35.23	33.72
1921	38.61	31.17	40.33	49.81

D. **Depreciation Allowances.**—All of the cost items grouped under *A*, *B*, and *C*, are paid out in cash, and most of them at frequent and regular intervals; for these reasons they can not easily be overlooked or misunderstood. But with regard to allowances for depreciation, obsolesence and raw material depletion the case is very different; these are not items of current outgo, but they are matters which accumulate over long periods and then are apt to come somewhat as a surprise.

Taking up first the matter of raw material depletion, we can see that a quarry will be exhausted some day, so that each ton of rock quarried should carry an allowance to cover this fact. What is rarely seen so clearly, however, is that this allowance has no relation whatever to the cost of the quarry; it should be based on the cost of buying *another* and equivalent quarry. For example, there is a rather important plant which now has perhaps five or ten years' supply of limestone. Its old

properties cost a few dollars per acre; a depletion charge on this basis might fairly be one-tenth cent per ton. But when the existing quarry is gone, there is now no other supply within say ten miles of the mill, and this new supply, under the circumstances, is likely to cost rather more than a few dollars per acre. So a replacement charge begun over ten years ago should have amounted not to one-tenth cent per ton, but to several cents.

It is hard to value the matter exactly, but to judge from my own acquaintance with the conditions at a very large number of mills, I should say that 90 per cent of the American mills have ample supplies—sufficient to run from 20 to 100 years or more—bought at very reasonable figures; and that the depletion allowance might range from a maximum of perhaps one cent a barrel down to one-tenth cent per ton of rock. On the other hand perhaps 10 per cent of existing mills will have to do something about new raw material supplies in the course of ten years; in such cases the depletion allowance should be fixed with reference not to the original cost of the old land, but to the cost of obtaining new properties.

As for plant depreciation, that is also intangible and uncertain. If no entirely new methods or processes appear within the next fifteen years, an allowance of 5 per cent of the actual cost of the old plant will be more than enough to cover normal depreciation, provided of course that the usual repairs are kept up from year to year. For the plants built before 1916, the allowance suggested would be equivalent to around five cents per barrel of cement produced; for plants built during the war-boom, it might amount to ten or even fifteen cents per barrel.

The range and trend of total costs.—If we add together the various partial costs whose details have been discussed above, we find a total cost which varies from mill to mill, but still more strikingly from year to year. This point is well shown in Table 214 following, which gives total costs at a large group of American mills, representing together around a quarter of the total American output of Portland cement. The table covers the period 1913 to 1921 inclusive; and like the preceding the costs are stated in cents per barrel.

It should be noted that the large group tabulated above represent about the lowest-cost large fraction of the American industry; for the American industry taken as a whole the average cost of cement shipped would be from 10 per cent to 20 per cent higher than the costs in Table 214, according to the year and to local conditions as regard coal, labor, etc.

TABLE 214.

TOTAL COSTS OF CEMENT MANUFACTURE, 1913–1921.

Year.	Total Costs per Barrel Shipped, Cents per Barrel.	Year.	Total Costs per Barrel Shipped, Cents per Barrel.
1913	73.4 cts.	1918	145.4 cts.
1914	73.14	1919	146.7
1915	69.6	1920	181.2
1916	79.8	1921	162.5
1917	112.9		

The course of cement prices, 1880–1920.—The course of Portland cement prices in the United States has shown very clearly the effects of various factors in the industry in the period 1880 to 1920.

At the outset, the price of Portland cement in our seaboard cities ranged from $2.50 to $3.50 per barrel during all the period prior to 1890. The bulk of our supply was imported at that time, and foreign makers fixed American prices by consequence. The effects of the gradual growth of the American industry are shown in the steady fall in prices as that industry came to take a larger and larger share of the home market. Up to around 1895 the American industry was still working along old lines of manufacture, and prices normally ranged between $2.00 and $2.50 per barrel, a striking testimony to the high manufacturing costs under old methods of burning.

From around 1895 onward the full effect of the rotary kiln method began to be shown in average costs and, by consequence, in average prices. Prices pitched down with scarcely an interruption, reaching an average of 88 cents per barrel in 1904 as compared with $1.62 as late as 1898. A little later there was renewed pressure on prices, owing in part to the adoption of the long kiln. The economies due to this improvement were, as has been stated earlier, relatively slight; but they brought about further price reductions as shown in table 215 below.

So far I have been speaking of nominal prices, as expressed in American currency. But the experience of the world since 1913 has convinced everyone that prices of any single commodity, expressed in currency values, are to a large extent unreal, because the currency itself is in course of fluctuation. In order to get a fair idea of what has happened to cement prices during the period 1890 to 1920, I have therefore calculated, in the last column of table 215, the real prices, which equal the nominal prices divided by the average price index of the year. This matter has been already discussed in the Introduction, on pages 7 and 9.

In Fig. 132 the real prices are shown graphically for the entire period 1890 to 1920, inclusive.

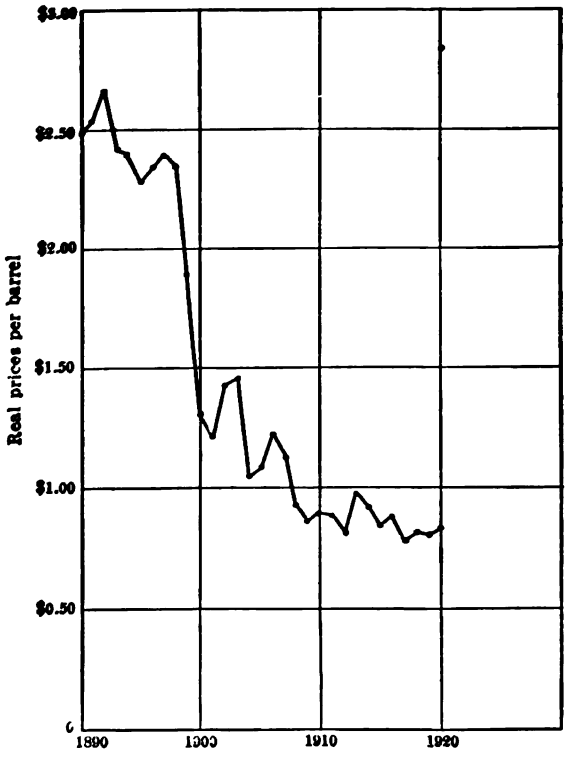

FIG. 132.—"Real" prices of Portland cement, 1890–1920; being currency prices reduced to true values by means of average price index.

The Production of Portland Cement

World's cement industry and output.—There are no precise data available as to the production of Portland cement throughout the world, and of course during very recent years the cement industry has been hopelessly disorganized, in most countries, less by the real war than by the semi-peace which followed. It is questionable if during any year since 1913, for example, the total world output has been as high as was reached in that year. Beginning with 1922 we may fairly expect a resumption of the growth of the cement industry, perhaps at something approaching its old rate of increase.

TABLE 215.

PRICES, NOMINAL AND REAL, OF PORTLAND CEMENT, 1890–1920.

Year.	Nominal Price per Barrel in Currency.	Index Number, Average Prices.	Relative or True Price.
1890	2.09	84	$2.49
1891	2.13	84	2.54
1892	2.11	79	2.67
1893	1.91	79	2.42
1894	1.73	72	2.40
1895	1.60	70	2.29
1896	1.57	67	2.35
1897	1.61	67	2.40
1898	1.62	69	2.35
1899	1.43	76	1.88
1900	1.09	83	1.31
1901	0.99	81	1.22
1902	1.21	84	1.44
1903	1.24	85	1.46
1904	0.88	84	1.05
1905	0.94	87	1.08
1906	1.13	92	1.23
1907	1.11	97	1.14
1908	0.85	92	0.924
1909	0.813	95	0.856
1910	0.891	99	0.900
1911	0.844	96	0.879
1912	0.813	100	0.813
1913	1.005	101	0.995
1914	0.927	100	0.927
1915	0.860	101	0.851
1916	1.103	124	0.889
1917	1.354	176	0.770
1918	1.596	196	0.814
1919	1.71	212	0.807
1920	2.01	244	0.829

The world's total output of hydraulic cements for the latest dates obtainable has been placed * at 37 million tons annually. Of course this total includes not only Portland, but natural, grappier and puzzolan cement, hydraulic lime, etc. There is no use attempting to make corrections for these less important hydraulic products; they reach their maximum importance in France, where the natural, slag and grappier cement output is something over one million tons, as against a Portland output of a little under one million. In most other countries Portland represents all or almost all of the cement now produced. We can fairly assume that in the years covered the amount of Portland cement alone reached 35 million metric tons. With reasonable luck

* Schultz, R. S. Cement in Foreign Countries, Min. Res. U. S. for 1918, vol. II. pp. 589–621.

in the way of reconstruction of industries and finances, the world will probably take at least 50 million tons of Portland cement by 1930.

The world total above stated was divided by continents as follows:

Europe	17,861,400	metric tons
North America	17,629,700	" "
Asia	1,049,300	" "
Australia	254,000	" "
Africa	152,400	" "
World total	37,038,200	metric tons

The more important producers, having a yearly output above 100,000 tons, are

United States	16,103,600	metric tons
British Empire	4,872,500	" "
France and colonies	2,058,400	" "
Belgium	2,032,000	" "
Germany	7,193,300	" "

In considering this last item we must recall that it is at present reduced to a considerable extent. France, Denmark and Poland have gained producing cement plants at the expense of the former German total. It is probable that at present the German Republic still holds second place as a producer, but it is also probable that this rank is held by a very narrow margin as against the British Empire and France. With the normal development of the British and French regions, it is questionable if Germany will rank higher than fourth by 1930.

The countries which will show the highest future rates of growth, aside from the United States and Canada, seem likely to be South Africa and Australia, both having adequate fuel supplies. Argentina and Brazil are cramped by lack of domestic coal supplies.

The American Portland-cement industry.—The Portland-cement industry of the United States dates back to around 1875, when the first attempts at American manufacture of that commodity took place. For twenty years the growth of the industry was at a rapid though not surprising rate. The adoption of the rotary kiln with powdered coal as fuel led, however, to a very remarkable rate of growth during the decade 1895 to 1905, as is shown by the percentages of increase calculated for the table below.

The end of this period of exceptional growth came in 1906; the imminence of the change was pointed out * by the present writer early in

* Engineering Magazine, January, 1907.

the following year. After its recovery from the financial crisis of 1907–8 the Portland cement industry recommenced its growth, but this time at rates corresponding quite closely to those of other great American industries. Hereafter it may be expected to keep in close touch with general industrial and business conditions; to advance when these are sound, to fall off temporarily when a financial crisis is on hand; but not to grow independently as it did during its period of youthful boom in 1895–1906.

The facts as to growth of the American industry during its whole history are shown most clearly when the rates of growth, by periods, are calculated and tabulated as in table 216 following:

TABLE 216.

GROWTH OF AMERICAN PORTLAND CEMENT INDUSTRY, 1880–1920.

Year.	Output, Barrels.	Period Covered.	Rate of Growth During Five-year Period, Per Cent.
1880	42,000	.....	....
1885	150,000	1880–1885	257
1890	335,500	1885–1890	124
1895	990,324	1890–1895	195
1900	8,482,020	1895–1900	757
1905	35,248,812	1900–1905	316
1910	76,549,951	1905–1910	117
1915	85,914,907	1910–1915	12
1920	100,302,000	1915–1920	17

The Canadian Portland-cement industry.—The first Canadian production of Portland cement was in 1890, but the industry did not grow rapidly until around 1900–1905. At first there was a large percentage made from a marl-clay mixture; this type of mix accounted for 28 per cent of the total output as late as 1911; but to-day the use of marl has fallen off sharply, and less than 2 per cent of the 1917 output was so produced.

The data in the following table are taken from the records of the Canadian Department of Mines:

TABLE 217.

CANADIAN OUTPUT OF PORTLAND CEMENT, 1890 TO DATE.

Calendar Year.	Barrels	Value.	Average Value.
1890	14,695	$17,583	$1.20
1891	2,633	5,082	1.93
1892	29,221	52,751	1.81
1893	31,924	63,848	2.00
1894	35,177	69,795	1.98
1895	62,075	112,880	1.82
1896	78,385	141,151	1.80
1897	119,763	209,380	1.75
1898	163,084	324,168	1.99
1899	255,366	513,983	2.01
1900	292,124	562,916	1.93
1901	317,066	565,615	1.78
1902	594,594	1,028,618	1.73
1903	627,741	1,150,592	1.83
1904	910,358	1,287,992	1.41
1905	1,346,548	1,913,740	1.42
1906	2,119,764	3,164,807	1.49
1907	2,436,903	3,777,328	1.55
1908	2,665,289	3,709,139	1.39
1909	4,067,709	5,345,802	1.31
1910	4,753,975	6,412,215	1.35
1911	5,692,915	7,644,537	1.34
1912	7,132,732	9,106,556	1.28
1913	8,658,805	11,019,418	1.27
1914	7,172,480	9,187,924	1.28
1915	5,681,032	6,977,024	1.23
1916	5,369,560	6,547,728	1.22
1917	4,768,488	7,724,246	1.62
1918	3,591,481	7,076,503	1.97
1919	.....	.....	.....
1920	.....	.....	.....

During the past decade or so the chief increases in Canadian cement consumption seem to have been in the Prairie Provinces, and this region is apt to continue to be a growing market for many years to come. The other Canadian region which offers great hopes for heavy increases in future is in the Maritime Provinces, where the proximity of the Sydney coalfield and the shipping facilities point toward the development of an export business. A good Nova Scotia mill to-day would have distinct advantages, as regards export to any South American country, as against any mill in the United States.

CHAPTER XXXVI.

CONSTITUTION, SETTING PROPERTIES, AND COMPOSITION OF PORTLAND CEMENT.

Limitations of chemical analyses.—An ordinary chemical analysis of a specimen of cement will determine what elements are present in the cement, and in what percentages these various constituents are represented. The comparison of a long series of such analyses, such as is presented later in this chapter, will enable certain conclusions to be drawn as to the probable limits of composition of good Portland cements; and an analysis of a single cement may show that it contains undesirable ingredients or that inert material is present in undesirable quantity. But these methods of investigation fail to give the least information concerning the real *constitution* of Portland cement as distinguished from its *composition;* they give no information whatever as to the manner in which the various elements are combined among themselves. They fail, moreover, to give any clue to the reason why certain mixtures give good cements, while others give weak or unsound products; and they afford no explanation of the "hydraulic" or setting properties which the powdered clinker possesses. It is evident, therefore, that other methods of investigation must be adopted, since even the most careful chemical analysis fails to aid us in this line of research.

Constitution and Setting Properties.

Available methods of investigation.—Two distinct methods of investigation are available—microscopic and synthetic.

The first has been applied with great success by geologists to the study of the igneous rocks, and as cement clinker is practically an artificial (though very basic) igneous rock, the microscope can be used successfully in its examination. By grinding normal clinker of known analysis down to thin transparent slices, the microscope is able to detect certain constituents common to all good clinkers. The next step, of course, is to determine the composition of these different constituents, and here the synthetic method is applicable.

In synthetic work pure lime, silica, alumina, etc., are mixed in certain definite proportions and burned to a clinker. The hydraulic properties of this clinker can be examined by powdering part of it and testing the resulting cement. Examination under the microscope will fix certain optical characters peculiar to each clinker composition, and the data thus obtained can be used to determine the constituents of commercial-cement clinker, as noted in the preceding paragraph.

Synthetic investigations.—Richardson has recently summarized the results of his own studies and those of previous observers as follows:

"The preparation of synthetic silicates and aluminates which might exist in Portland cement was carried out to a certain extent by Le Chatelier and the Newberrys, but in neither case were these compounds characterized completely, especially as to their optical properties. This has been done by the writer within the last two years, and the optical properties and other characteristics of the following definite silicates and aluminates have been determined.

"Monocalcic silicate (SiO_2CaO): A crystalline substance of high optical activity and little or no hydraulic properties. Specific gravity 2.90.

"Dicalcic silicate (SiO_22CaO, or more probably $2Si_24CaO$): A definite crystalline compound of high optical activity and of very little hydraulic activity except in the presence of carbonic acid, but setting slowly in water, generally lacking volume constancy. Specific gravity 3.29.

"Tricalcic silicate (SiO_23CaO): A definite crystalline silicate of low optical activity and corresponding in this respect with alit. Its hydraulic activity is not great, but greater than that of dicalcic silicate. If fused and reground it sets slowly like Portland cement. Specific gravity 3.03.

"Three definite silicates of calcium, therefore, appear to exist, the two more basic ones being strongly differentiated from each other by their optical activity.

"Monocalcic aluminate (Al_2O_3CaO): This aluminate is a crystalline substance of high optical activity, but is not sufficiently basic to permit of its existence in a material of such basic character as Portland-cement clinker. Specific gravity 2.90.

"Tricalcic dialuminate ($2Al_2O_33CaO$): This aluminate is one of highly crystalline character and of great optical activity, making it readily recognizable. Specific gravity 2.92.

"Dicalcic aluminate (Al_2O_32CaO): A substance crystallizing from a state of fusion in dendritic forms having no optical activity and being,

therefore, isotropic. This differentiates this aluminate very sharply from the preceding one and makes the identification of the two materials very easy. Specific gravity 2.79.

" Tricalcic aluminate ($Al_2O_3 3CaO$): This aluminate crystallizes from the fused condition in elongated octahedra. It is isotropic and it might at first be assumed that it was not a definite compound, but merely the dicalcic aluminate crystallizing out of a magma of indefinite composition. It has been shown, however, by further investigations too lengthy to go into at this point, to be undoubtedly a definite aluminate. Specific gravity 2.91.

" Definite compounds of iron and lime and alumina and magnesia have also been shown to exist, but their consideration here is unnecessary, as the constitution of Portland cement can be better discussed, theoretically, by a study of clinker, into which these elements do not enter.

" Among the theories advanced as to the constitution of Portland cement there are those which assume the presence of certain so-called silico aluminates, such as $2SiO_2$, $2Al_2O_3$, $6CaO$, and others of less basic form. All of these proposed compounds have been prepared by the writer and found not to be definite chemical compounds nor to correspond in any way with any of the mineral entities found in industrial clinker. They are in fact only solid solutions, of aluminates in silicates, of indefinite structure."

Microscopic investigations.—Le Chatelier, Törnebohm, and Richardson have studied both industrial and synthetic clinker under the microscope, and the results of these preliminary studies have thus been summarized by the last-named investigator:

" By this method of study Le Chatelier, and, at the same time independently of him, Törnebohm, identified in Portland-cement clinker four distinct mineral constituents which Törnebohm described as follows, naming them Alit, Belit, Celit and Felit:

" Alit is the preponderating element and consist of colorless crystals of rather strong refractive power, but of weak double refraction. By this he means that alit in polarized light between crossed nicol prisms has insufficient optical activity to produce more than weak bluish gray interference colors.

" Celit is recognized by its deep color, brownish orange. It fills the interstices between the other constituents, being the magma or liquid of lowest freezing-point out of which the alit is separated. It is strongly double refractive, that is to say, gives brilliant colors when examined between crossed nicol prisms.

"Belit is recognized by its dirty green and somewhat muddy color and by its brilliant interference colors. It is biaxial and of high index of refraction. It forms small round grains of no recognized crystalline character.

"Felit is colorless. Its index of refraction is nearly the same as that of belit and it is strongly double refractive. It occurs in the form of round grains, often in elongated form, but without crystalline outline. Felit may be entirely wanting.

"Besides these minerals an amorphous isotropic mass was detected by Törnebohm and Le Chatelier. It has a very high refractive index.

"Törnebohm adds the important fact that a cement 4 per cent richer in lime than usual consists almost entirely of alit and celit."

Theories of constitution.—Until recently Portland-cement clinker was commonly assumed to be a mixture of two or more definite chemical compounds, and the principal points at issue between various investigators were: (1) the exact formulas for these compounds, and (2) the proportion in which they must exist to give a good Portland cement. The two theories, in this regard, that have made the most impression upon modern cement practice are those presented respectively by Le Chatelier and Newberry. Recently, however, Richardson has formulated a theory of entirely different type. These three explanations of the constitution of Portland clinker will, therefore, be described briefly.

Le Chatelier, speaking of Portland-cement clinkers, states * that:

"Examined in thin plates under the microscope they are formed of tricalcic silicate in crystals, with very feeble double refraction, embedded in a crystalline ground-mass of silico-alumina—ferrites of lime. These are the two essential elements of Portland cement. If the lime is in excess, aluminate of lime is first formed; then for a still greater excess, ferrite of lime, and finally free lime. If, on the other hand, the lime is deficient in quantity, a dicalcic silicate is formed, recognizable by the spontaneous crumbling of the burnt pieces of cement. When the mixture is imperfect or the burning insufficient, the reactions remain incomplete, and although the average composition may be suitable, there is a simultaneous production of free lime and aluminate of calcium with dicalcic silicate. In a Portland cement of normal composition the proportion of lime, according to the chemical formulas of the compound, should be greater than that determined by the following formula:

$$\frac{SiO_2 - Al_2O_3 - Fe_2O_3}{CaO} > 3, \quad \ldots\ldots \quad (1)$$

* Trans. Amer. Inst. Mining Engineers, vol. 22, pp. 3–52.

in which CaO, SiO_2, Al_2O_3, Fe_2O_3 represent not the equivalent weights but the number of equivalents of these substances present; that is to say, the quotients of the weights of the substances divided by their equivalent weights.* This proportion of lime must never, on the other hand, reach the relation indicated by the following formula:

$$\frac{CaO}{SiO_2+Al_2O_3-Fe_2O_3}<3, \quad \ldots\ldots \quad (2)$$

which corresponds to the exclusive formation of aluminate of calcium. It is necessary, by reason of the inevitable imperfection of the mixture, to keep always well below this limit, beyond which there will remain uncombined lime. In the use of this formula, magnesia should be added to the lime and sulphuric acid to the denominator after dividing its number of equivalents by 3."

On a later page Le Chatelier states that Portland cements of good quality would give a value between 3.5 and 4.0 for formula 1, and between 2.5 and 2.7 for formula 2.

The Newberrys, working on synthetic cements prepared from pure raw materials, obtained results differing from those of Le Chatelier in one important particular. They agreed with him that the lime and silica combined in the form of the tricalcic silicate $3CaO.SiO_2$; but in regard to the lime-alumina compound they decided that it was present as the dicalcic aluminate $2CaO.Al_2O_3$ instead of in the tricalcic form given by Le Chatelier. These results gave, as the general formula for a pure Portland,

$$x(3CaO.SiO_2)+y(2CaO.Al_2O_3).$$

No allowance is made for magnesia, as the experimenters decided that it could not give a hydraulic product if present in Portland cement; while iron is neglected because of the small percentage in which it usually occurs.

Richardson, working both with the microscope and with synthetic preparations, has evolved a theory of much ingenuity and complexity by treating the investigation as a study in solid solutions. For the details of this remarkable and important work reference should be made to his original papers.† In the present place only a brief summary of his principal conclusions can be given.

He believes that the two principal constituents of a good Portland-cement clinker are the materials identified under the microscope by Törnebohm and named alit and celit; that alit is a solid solution

* For a table of combining weights, see p. 11 of this volume.

† See list on p. 519.

of tricalcic aluminate ($3CaO.Al_2O_3$) in tricalcic silicate ($CaO.SiO_2$), while celit is a solid solution of dicalcic aluminate ($2CaO.Al_2O_3$) in dicalcic silicate ($2CaO.SiO_2$).

"Having determined that alit and celit are solid solutions of aluminates in silicates, the aluminates being present in less than an amount sufficient to make a saturated solution of aluminate in the silicate, it becomes of interest to consider how these solutions are formed during the conversion of a raw mixture or of a mixture of pure chemicals into a clinker. It would be simple to understand this if fusion took place in its formation, but this does not happen, the material is only sintered. If two gases are brought together they diffuse into each other with very great rapidity. If two liquids are poured one upon the other in layers without mixing, they diffuse more slowly. If solids are brought into contact it would be naturally assumed that diffusion would cease. Experiments of Robert-Austen have shown that molecular mobility in solids exists, since when carefully polished surfaces of gold and lead are brought into contact and left under pressure for some months, at the ordinary temperatures, gold is diffused into the lead and the lead into the gold for an appreciable distance. Mixtures of the components which would produce a fusible wood metal when subjected to pressure at ordinary temperature become converted into this alloy. Anhydrous sulphate of soda and carbonate of barium also diffuse when brought into close contact with the formation of barium sulphate and carbonate of soda. It is not difficult to understand, therefore, how at a temperature of 1650° C. the particles of silica, alumina, and lime may diffuse below the melting-point of the resulting clinker to form a Portland cement, and the fact that such a clinker is stable depends not only on its composition, but upon the fact that the diffusion has been complete, even in material which is only sintered. Sintering, therefore, may be defined as diffusion at a temperature below the melting-point of the components or of the resulting solid solution. That diffusion under such conditions is surprisingly rapid is seen by placing a particle of ferric oxide on the surface of white Portland-cement clinker, and then submitting it to a moderately high temperature. The rapid diffusion of iron through the white clinker can readily be noticed by the color which spreads through the mass. It is evident that the higher the temperature the more rapid the diffusion until it becomes very rapid on fusion. From this it may be concluded that the length of time during which it is necessary to expose any mixture of silica alumina and lime to a temperature is a function of the temperature, and should be longer, the lower the temperature."

Recent investigations.—In recent years the most important work done along these lines has been that carried on by Rankin and others at the Geophysical Laboratory of the Carnegie Institution, and at the U. S. Bureau of Standards. The summary following, which brings up to date our knowledge of the constitution or normal Portland cements, is based upon the work of Rankin later cited. It will be seen that, so far as active constituents are concerned, these recent investigations take us back again to the ideas of Le Chatelier. They are, however, based on a far broader range of experiments under varying conditions, carried out with great precision; and they will ultimately lead in the direction of improved cements.

The essential components of a normal Portland cement, disregarding the presence of magnesia and iron oxide are, according to Rankin, tricalcic silicate, dicalcic silicate and tricalcic aluminate.

When a mixture made up only of lime carbonate, silica and alumina is heated the first change is the evolution of carbon dioxide. The lime then unites with the other components to form the two compounds $5CaO,3Al_2O_3$, and $2CaO,SiO_2$. Subsequently these two unite in part with more lime to form $3CaO,SiO_2$ and $3CaO,Al_2O_3$. As the temperature rises more and complete combination occurs, with the final result that a perfectly burned clinker contains only dicalcic and tricalcic silicates, and tricalcic aluminate. The table following (218) gives data on the compounds actually present under both theoretical and commercial conditions:

TABLE 218.

COMPOSITIONS AND BURNING TEMPERATURES OF PORTLAND CEMENTS.

Portland Cements.	Actual Components.	Burning Temperature, Deg. C.	Constituents of Resulting Cements.
Pure	CaO.....68.4 Al_2O_3..... 8.0 } 100.0 SiO_2.....23.6	1650	$2CaO.SiO_2$ $3CaO.SiO_2$ $3CaO.Al_2O_3$
White	CaO.....66.2 Al_2O_3..... 6.4 } 97.6 SiO_2.....25.0 MgO, Fe_2O_3, Na_2O and K_2O..... 2.4	1525	$2CaO.SiO_2$ $3CaO.SiO_2$ $3CaO.Al_2O_3$ } Small amount of CaO
Commercial gray	CaO.....63.2 Al_2O_3..... 7.7 } 93.3 SiO_2.....22.4 MgO, Fe_2O_3, Na_2O, K_2O and SO_3.... 6.7	1425	$2CaO.SiO_2$ $3CaO.SiO_2$ $3CaO.Al_2O_3$ } Small amounts of $5CaO.3Al_2O_3CaO$ and ferrites

In the first edition of the present volume, published some fifteen years ago, the author suggested that there was no reason to assume that the composition of our normal commercial Portland represented the best attainable, and consequently treated Portland cement as an attempt to secure a pure tricalcic silicate. This idea, at that date somewhat unusual, is now accepted quite broadly. Furthermore, there was the suggestion that we might come to make cements of Portland type, but specially high in alumina, in iron oxide or in magnesia—all for special uses. These things also have come to pass, and the special high-alumina and high-iron Portlands are discussed in the present edition on pages 517–519.

Setting properties of Portland cement.—The theory which has been quite generally accepted as explaining the setting of Portland cement was that advanced by Le Chatelier. He considered that the aluminate of lime, in contact with water, hydrated and hardened like plaster, according to the equation:

$$3CaO.Al_2O_3+12H_2O=3CaO.Al_2O_3.12H_2O.$$

To this action of the aluminate was ascribed the initial set of the cement. The later hardening was ascribed, however, to the decomposition of the lime silicate. In contact with water it sets, dividing so as to give hydrated monocalcic silicate crystallizing in microscopic needles, and calcium hydrate crystallizing in large hexagonal plates:

$$3CaO.SiO_2+\text{water}=CaO.SiO_2.2\tfrac{1}{2}H_2O+2(CaO.H_2O).$$

In general this theory, has been accepted.

Richardson, however, has recently modified * this theory in an important way. He considers that the setting of Portland cement is due to the decomposition of the silicates and aluminates of the clinker by the action of water, producing lime hydrate ($Ca_2H_2.O_2$) in a peculiarly active form.

" On the addition of water to a stable system made up of the solid solutions which composed Portland cement a new component is introduced which immediately results in a lack of equilibrium, which is only brought about again by the liberation of free lime. This free lime the moment that it is liberated is in solution in the water, but owing to the rapidity with which it is liberated from the aluminate, the water soon becomes supersaturated with calcic hydrate, and the latter crystallizes

* Richardson C. The setting or hydration of Portland cement. Engineering News, vol. 53, pp. 84–85. Jan. 26, 1905.

out in a network of crystals which binds the particles of undecomposed Portland cement together. From the characteristics of the silicates and aluminates it is evident that the latter are acted upon much more rapidly than the silicates, and it is to the crystallization of the lime from the aluminates that the first or initial set must be attributed. Subsequent hardening is due to the slower liberation of lime from the silicates. If the lime is liberated more rapidly than is possible for it to crystallize out from the water, expansion ensues and the cement is not volume constant."

He further notes that of the two constituents of the clinker the celit is almost inert, being usually unattacked by the water, while the alit furnishes most of the lime needed for the setting effect. As the celit is a solution of dicalcic salts ($2CaO.SiO_2+2CaO.Al_2O_3$), while the alit is a solution of tricalcic compounds ($3CaO.SiO_2+3CaO.Al_2O_3$), the lower-limed cements are, therefore, the less hydraulic. This agrees with experience.

This theory differs from Le Chatelier's in that it considers setting as due only indirectly to the presence of silicates and aluminates.

" The strength of the Portland cement after setting is due entirely to the crystallization of calcium hydrate under certain favorable conditions, and not at all to the hydration of the silicates or the aluminates, since in this act of hydration nothing can take place which would tend to bind these silicates and aluminates together."

The formation of lime silicates and aluminates during clinkering is on this theory only a convenient way of securing indirectly a very active lime hydrate, which is itself the real cementing material.

Replacement of silica by other acids.—Various oxides of the silica group have been substituted by Richardson in his series of synthetic cements. Titanic oxide (TiO_2), stannic oxide ($SnO)_2$, and plumbic oxide (PbO) have been so used. " The ground clinker in each case has been found to set rapidly, although the resulting test pieces were not volume constant, the temperature obtainable in our furnace being evidently insufficient to bring about a thorough combination between these oxides and lime. Cements have been made in which phosphoric acid (P_2O_3) has been substituted for silica."

Replacement of alumina by iron oxide.—Some difference of opinion appears concerning the extent to which the alumina of a Portland cement may be replaced by iron oxide.

This problem was taken up by the Newberrys in the classic researches before cited. They prepared mixtures of pure iron oxide and calcium carbonate in such proportions as to correspond to the formula 3CaO.-

Fe_2O_3, which in percentages is equivalent to CaO 41.3 per cent, Fe_2O_3 58.7 per cent. "On burning, the material fused to a black slag, which yielded a brown color on grinding. Mixed with water to a paste, this powder showed no heating, and did not set or harden in air or cold water. A part placed in steam, however, after setting one day in air, hardened rapidly, and after several hours in boiling water showed no cracking and appeared very hard. From this experiment it appears that lime and iron oxide readily combine, yielding a product which is constant in volume, though it shows no hardening properties in the cold." The Newberrys carry the experiments further, making a silica-, iron oxide, lime mixture entirely free from alumina. This was made to correspond to the formula

$$(3CaO.SiO_2)+\times(2CaO.Fe_2O_3),$$

and contained about 7 per cent of iron oxide. On burning this gave a black, fusible clinker. When powdered this was dark-gray, and gave a slow-setting hard and sound cement.

Their final conclusions were, that though "iron oxide evidently combines with lime in the same manner as alumina," the amount of iron oxide present in ordinary clays is so small that "it is quite unnecessary, in working with ordinary clays, to take the iron oxide into consideration in calculating the amount of lime required."

In view of the manufacture of cements containing appreciable percentages of iron oxide, it seems advisable to take this constituent into consideration in proportioning mixes, and this has accordingly been done in the formula given earlier in this volume.

Replacement of lime by magnesia.—The possibility of this replacement has been flatly denied by some of our leading authorities on cement chemistry, while it has been maintained, but less confidently, by others. To the present writer it seems certain that magnesia is absolutely interchangeable with lime, due regard being paid to their differences in atomic weight. It is only necessary to adduce the example of the high-burned natural cements, such as the Akron, to make it clear that a cement containing 15 to 20 per cent of magnesia can be made at almost clinkering temperature. Recent experiments by Newberry seem to confirm this conclusion. It is to be noted, however, that a Portland cement carrying high percentages of magnesia will necessarily differ considerably from the present-day lime Portlands. It is even probable that the differences in physical and technical properties will be so great that it will be necessary to market such magnesia Portlands under some distinct trade-name.

Replacement of lime by other bases.—Magnesia is not the only base that can replace, either partly or entirely, the lime of a normal Portland-cement clinker. Other alkaline earths can be so substituted, as was proven in the course of Richardson's recent experiments. He describes * this phase of his work as follows:

"Clinkers have been made in which baryta (BaO) and strontia (SrI) are the bases. They must be burned at a very much higher temperature than similar clinkers containing lime. In powder these (barium and strontium cements) possess strong hydraulic properties, and are volume constant in water for a few days, but owing to the greater solubility in water of barium and strontium hydrate than of lime hydrate, the material after setting is much more readily attacked by water than is lime cement, strontium hydrate being about twice as soluble as calcium hydrate, and barium hydrate about eight times as soluble."

High-alumina Portlands.—The normal commercial Portland cement, being made by use of clay, shale or slag as its argillaceous component, is necessarily limited in its iron-alumina-silica ratio by the ordinary composition of its raw materials. The ratio of alumina to iron oxide, in particular, commonly falls between the limits 2 : 1 and 3 : 1, though it may range outside, in both directions.

In the white Portlands, made by use of clays low in iron, the alumina content is appreciably higher. But in such cements as Spackman's *alca cement*, and Lafarge's *ciment fondu*, the alumina becomes the main cement component, combined of course with lime as a base.

The *ciment fondu*, or *fused cement*, is made from a mix of limestone and bauxite and is actually fused in a blast-furnace or an electric furnace. Its rapid adoption in France is due to certain special properties; very rapid hardening, which permits withdrawal of centers or supports from concrete work in a day or two; resistance to sea-water and alkaline solutions; white color. For description of these reference is made to the papers by Candlot and Eckel cited on page 519. The *alca* series of cements worked out by Spackman has been described in many papers, noted on page 520. It is made from an aluminous slag, and therefore carries less alumina and more silica than does the ciment fondu.

High-iron Portlands.—Diverging from normal Portlands in a direction opposite to that of the high-alumina products just discussed, we have the high-iron cements, that have been made commercially in Europe and experimented with in America.

These high-iron Portlands or ferro-Portlands use, in place of clay

* Engineering News, vol. 53, p. 85. Jan. 26, 1905.

or shale, some source of iron oxide in their mix. Michaelis has used iron ore for this purpose, securing by that means the iron-cements whose analyses are quoted in Table 219 following. American experiments with greensand, a natural potash-iron silicate, gave the iron-cements whose analyses are in Table 220.

One point to be noted is that the burning of the iron cements takes place at a materially lower temperature than the burning of the normal Portlands. This is, of course, an advantage, but it is partly compensated for by the fact that in dealing with a cement mixture rich in iron the sintering and fusing points of the mixtures are quite close together. Until the burner becomes accustomed to the mixture he is therefore likely to overburn the clinker, so as to give a very hard and partly or completely fused product. When proper burning has once been established, however, the same kiln will yield an appreciable higher output per day of iron cement than of normal Portland.

The analyses of Table 219, of ferro-Portland made by the use of iron ore are fairly representative of the type. It must be said, however, that many of the cements made by the Michaelis process at the Hemmoor plant approximate much more closely to the pure ferrite type than do these analyses, usually carrying only 1 to 2 per cent of alumina.

TABLE 219.

ANALYSES OF FERRO-PORTLAND, MICHAELIS TYPE.

	Per Cent.	Per Cent.	Per Cent.
Silica	23.44	19.47	20.42
Alumina	2.98	3.47	3.39
Iron oxide	7.48	9.44	6.47
Lime	61.86	63.50	63.48
Magnesia	0.50	0.64	0.30
Sulphur trioxide	1.72	*2.15	*2.01
Ignition loss	0.69	0.78	1.48

* Calcium sulphate.

For comparison with the above analyses, a series of analyses of ferro-Portlands made by the use of greensand are presented in Table 220.

The high-iron cements are dark colored and very slow-setting; they are specially resistant to sea-water.

References on constitution of Portland cement.—The following list will serve as an introduction to the mass of literature on this subject. The items marked *C* refer to constitution of normal Portlands; those marked *A* to high-alumina cements; those marked *F* to high-iron

cements. The original papers by Vicat are cited; they are often overlooked by investigators educated in central Europe.

TABLE 220.

ANALYSES OF FERRO-PORTLAND.

Constituent.	Cement 1.	Cement 2.	Cement 3.	Cement 4.
Silica	20.37	19.52	22.76	22.98
Alumina	3.64	3.30	5.56	5.92
Iron oxide	8.97	7.38	8.50	8.36
Lime	61.42	62.62	56.59	56.92
Magnesia	0.82	4.12	3.39	3.33
Sulphur trioxide	1.19	0.42	0.59	0.55
Ignition loss	1.07	1.48	1.00	0.40
Cementation Index	1.08	0.93	1.23	1.25

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A. Spackman, H. S. Aluminates . . . in cement manufacture. Proc. Amer. Soc. Testing Materials, vol. 10. 1910.
C. Vicat, L. J. Recherches experimentales sur les chaux . . . Paris, 1818.
C. Vicat, L. J. Traité pratique et théorique de la composition des mortiers, ciments. . . . 4to, pp. 103, Grenoble. 1856.

Composition of Portland cements.—The chemical composition of Portland cements has been changing slowly in one direction since 1850. This is well brought out by the analyses of old Portland cements given in the following table, when compared with the analyses of modern Portlands given in Table 222.

TABLE 221.

ANALYSES OF PORTLAND CEMENT, 1849–1873.

	1.	2.	3.	4.
Silica (SiO_2)	18.60	22.23	23.72	18.60
Alumina (Al_2O_3)	11.30	7.75	7.36	4.75
Iron oxide (Fe_2O_3)	17.90	5.30	5.05	5.60
Lime (CaO)	49.80	54.11	54.40	58.50
Magnesia (MgO)	0.70	0.75	0.86	2.55
Alkalies (K_2O,Na_2O)	n. d.	1.76	2.62	1.70
Sulphur trioxide (SO_3)	n. d.	1.00	1.12	2.10
Carbon dioxide (CO_2)	n. d.	2.15	2.80	0.50
Water	n. d.	1.00	0.96	0.50

1. Manufactured about 1873 by I. C. Johnson & Co., England. Reports Vienna Exposition, vol. 4, pt. D, p. 35.
2. Manufactured about 1849 in England. Analyzed by Pettenkofer. Proc. Institution Civil Engineers, vol. 62, p. 77.
3. Manufactured about 1873 in England. Analyzed by Feichtinger. Reports Vienna Exposition, vol. 4, pt. D, p. 37.
4. Manufactured about 1873 in Austria. Analyzed by Wagner. Reports Vienna Exposition, vol. 4, pt. D, p. 37.

From inspection of the above table it will be seen that old Portlands were very low-limed products. Some, in fact, were too low in lime to be considered, at the present day, as falling in the Portland class.

Composition of American Portland cements.—Table 222, containing a large series of analyses of American Portland cements, has been compiled by the writer from various sources. About half of the analyses contained in it have already been published in different books and periodicals, while for the remainder the writer is indebted to the chemists of the various plants.

TABLE 222.

ANALYSES OF AMERICAN PORTLAND CEMENTS.

State.	Brand.	Company.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alk.	SO_3
Alabama	Red Diamond	Alabama P. C. Co	19.56	12.16		62.27	0.64	.....	0.54
"	" "	" "	19.91	13.63		63.82	0.83	.....	1.16
"	" "	" "	20.25	13.44		63.60	1.03	.....	0.41
"	" "	" "	19.99	13.74		61.36	0.61		
"	" "	" "	20.54	8.55	3.84	63.85	0.66		
Arkansas	Setter	Whitecliffs P. C. Co	22.93	10.33		64.67	0.94	.....	1.05
California	Golden Gate	Pacific P. C. Co	22.57	10.64		62.61	1.27	.....	1.32
"	" "	" "	22.40	10.76		63.10	1.22	.....	1.15
"	" "	" "	22.44	10.52		63.05	1.51	.....	0.78
"	" "	" "	22.25	7.65	3.35	62.85	0.78	0.69	1.34
"	Colton	California P. C. Co	21.1	12.9		63.5	0.7	.....	1.6
"	Santa Cruz	" " "	23.48	8.47	5.18	61.91	n. d.	0.92	n. d.
Colorado	Ideal	Colorado P. C. Co	21.60	8.04	2.82	64.35	1.08	.....	1.47
Illinois	Owl	German-American P. C. Co	24.12	9.78		61.45	2.56	.....	1.23
"	"	" " "	23.09	5.13	3.52	64.36	2.43	.....	1.53
Indiana	South Bend	Millens P. C. Works	22.30	7.21	3.79	59.24	3.03	.....	1.47
"	Wabash	Wabash P. C. Co	21.78	7.31	2.65	62.35	2.88	0.47	1.78
"	Sandusky	Sandusky P. C. Co	22.06	4.80	1.66	65.44	2.82	.....	0.90
Missouri	Red Wing	St. Louis P. C. Co	22.50	6.20	2.50	64.80	0.75	.....	1.15
Michigan	Wyandotte	Michigan Alkali Co	22.50	10.90		60.95	1.32	0.68	2.50
"	"	" " "	24.00	7.50	2.40	62.00	2.50	.....	1.50
"	Wolverine	Michigan P. C. Co	21.02	7.51	3.83	63.95	1.05	0.98	1.50
"	Alpena	Alpena P. C. Co	20.26	8.62	2.71	63.22	2.34	1.34	0.76
"	Bronson	Bronson P. C. Co	20.95	9.74	3.12	63.17	0.75	.....	0.86
"	Peerless	Peerless P. C. Co	20.65	11.08		65.40	1.95	.....	0.37
"	Peninsular	Peninsular P. C. Co	22.56	10.96		62.72	2.20	.....	1.50
"	Omega	Omega P. C. Co	24.24	7.26	2.54	64.96	2.26	.....	0.41
New Jersey	Alpha	Alpha P. C. Co	20.54	10.54		62.92	2.73	.....	1.21
" "	"	" "	21.70	8.88		63.27	0.55		
" "	"	" "	22.62	8.76	2.66	61.46	2.92	.....	1.52
" "	"	" "	22.89	8.00	2.44	63.38	2.30		

TABLE 222—(*Continued*).

ANALYSES OF AMERICAN PORTLAND CEMENTS.

State.	Brand.	Company.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alk.	SO_3
New Jersey	Edison	Edison P. C. Co	20.14	7.51	3.33	62.71	2.34	.....	1.64
" "	Vulcanite	Vulcanite P. C. Co	21.08	7.86	2.48	63.68	2.62	.....	1.25
New York	Catskill	Catskill P. C. Co	22.48	6.52	4.46	62.93	1.48	.....	1.30
" "	"	" "	21.94	6.02	4.38	64.62	1.25	.....	1.12
" "	"	" "	23.44	6.35	3.99	63.21	1.15	.....	1.22
" "	Empire	Empire P. C. Co	20.80	7.39	2.61	64.00	n. d.	.....	n. d.
" "	"	" "	22.04	6.45	3.41	60.92	3.53	.....	2.73
" "	"	" "	21.98	8.20	3.70	61.83	1.43	0.84	1.18
" "	Iron Clad	Glens Falls P. C. Co	21.50	10.50		63.50	1.80	0.40	1.50
						61.78	1.27		1.53
" "	Hudson	Hudson P. C. Co	21.60	9.27	3.80				
" "	Jordan	American C. Co	21.86	7.17	3.73	61.14	2.34	.....	1.94
" "	Millen's	Wayland C. Co	21.08	9.56		64.68	1.85	0.90	1.93
" "	"	" "	22.19	9.72		63.08	2.04	1.22	1.75
Ohio	Alma	Alma P. C. Co	21.63	6.70	4.75	63.58	1.10	.....	1.15
"	Buckeye	Buckeye P. C. Co	21.20	6.05	3.33	58.07	2.80	2.20	
"	"	" "	20.75	13.50		62.25	0.25	2.25	0.25
"	Diamond	Diamond P. C. Co	21.80	7.95	4.95	61.90	1.64	.....	0.79
"	"	" "	22.31	6.97	4.28	63.10	0.38	1.31	0.84
"	Ironton	Ironton P. C. Co	21.04	11.78		63.80	n. d.	.....	1.38
Pennsylvania	Atlas	Atlas P. C. Co	21.96	8.29	2.67	60.52	3.43	.....	1.49
"	"	" "	21.30	7.65	2.85	60.95	2.95	1.15	1.81
"	Dragon	Lawrence P. C. Co	20.87	7.60	2.66	63.04	2.80	.....	1.50
"	Giant	American C. Co	23.26	8.07	4.83	59.28	1.00	0.50	0.50
"	"	" "	20.99	4.12	5.18	60.75	0.41	.....	1.40
"	"	" "	19.92	9.83	2.63	60.32	3.12	.....	1.13
"	"	" "	22.08	8.52	4.81	62.12	1.71		
"	"	" "	22.45	13.23		61.37	0.66	0.71	1.37
"	"	" "	22.90	12.10		60.13			
"	Lehigh	Lehigh P. C. Co	21.04	10.46		62.46	2.56	.....	1.56
"	"	" "	22.61	9.55		62.45	2.61	.....	1.45
"	"	" "	22.29	9.48		62.54	2.49	.....	1.51

TABLE 222—(*Continued*).

ANALYSES OF AMERICAN PORTLAND CEMENTS.

State.	Brand.	Company.	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Alk.	SO_3
Pennsylvania....	Lehigh.....	Lehigh P. C. Co.....	22.13	9.56		62.63	2.51	.....	1.49
"	"	" "	22.00	9.74		62.34	2.54	.....	1.40
"	"	" "	22.19	10.18		62.39	2.62	.....	1.53
"	"	" "	22.26	9.49		62.46	2.65	.....	1.56
"	Nazareth.....	Nazareth P. C. Co.....	19.06	7.47	2.29	61.23	2.83	1.41	1.34
"	Phœnix.....	Phœnix P. C. Co.....	21.65	8.09	2.93	63.10	2.00	.....	1.02
"	Northampton.....	Northampton P. C. Co.....	21.18	7.03	2.41	63.06	2.05		
"	Reading.....	Reading C. Co.....	24.23	4.80	1.86	63.01	3.20	.....	1.20
"	"	" "	24.48	4.51	2.68	64.33	2.59	.....	1.41
"	Saylors.....	Saylors P. C. Co.....	22.04	10.11	1.61	62.93	1.13	.....	1.78
"	"	" "	22.68	6.71	2.35	62.30	3.41	.....	1.88
"	"	" "	21.25	8.25	4.21	61.25	1.50	2.00	1.38
South Dakota....	Yankton.....	Western P. C. Co.....	22.00	7.74	4.61	59.50	0.90	1.20	0.80
" "	"	" "	21.80	11.86		60.00	0.80	1.80	2.86
Texas.....	Live Oak.....	Texas P. C. Co.....	22.50	8.35	4.25	62.35	.....	.....	1.75
Virginia.....	Old Dominion.....	Virginia P. C. Co.....	21.20	7.90	2.82	63.14	2.40	.....	1.37
"	" "	" "	22.01	8.40	3.07	63.68	1.52	.....	0.54
"	" "	" "	20.65	6.93	2.76	63.47	2.76	.....	1.34

Standard Methods of Analysis.

The following methods of analysis are those suggested by a committee of the New York section, Society of Chemical Industry, consisting of W. F. Hillebrand and Clifford Richardson. For exact work it is desirable that these methods be closely followed. They are not intended for use in making the rapid determinations which are necessary for the control of the mix when the plant is in operation. A method of rapid analysis has recently been published by several members of the Lehigh section, American Chemical Society, which is probably well adapted for use in the Lehigh cement district; but it is doubtful if it is worth while attempting to formulate standard methods for rapid analysis, since the requirements vary so much at the different plants.

Method Suggested for the Analysis of Limestones, Raw Mixtures and Portland Cements.*

Solution.—One-half gram of the finely powdered substance is to be weighed out and, if a limestone or unburned mixture, strongly ignited in a covered platinum crucible over a strong blast for fifteen minutes, or longer if the blast is not powerful enough to affect complete conversion to a cement in this time. It is then transferred to an evaporating dish, preferably of platinum for the sake of celerity in evaporation, moistened with enough water to prevent lumping, and 5 to 10 c.c. of strong HCl added and digested, with the aid of gentle heat and agitation until solution is completed. Solution may be aided by light pressure with the flattened end of a glass rod.† The solution is then evaporated to dryness, as far as this may be possible on the steam-bath.

Silica.—The residue, without further heating, is treated at first with 5 to 10 c.c. of strong HCl, which is then diluted to half strength or less, or upon the residue may be poured at once a larger volume of acid of half strength. The dish is then covered and digestion allowed to go on for ten minutes on the bath, after which the solution is filtered and the separated silica washed thoroughly with water. The filtrate is again evaporated to dryness, the residue, without further heating, taken up with acid and water, and the small amount of silica it contains separated on another filter-paper. The papers containing the

* Eng. News, 50, p. 60. Eng. Record, 48, p. 49. Cement, Sept., 1903.

† If anything remains undecomposed it should be separated, fused with a little Na_2CO_3, dissolved and added to the original solution. Of course, a small amount of the separated non-gelatinous silica is not to be mistaken for undecomposed matter.

residue are transferred wet to a weighed platinum crucible, dried, ignited, first over a Bunsen burner until the carbon of the filter is completely consumed, and finally over the blast for fifteen minutes and checked by a further blasting for ten minutes or to constant weight. The silica, if great accuracy is desired, is treated in the crucible with about 10 c.c. of HFl and four drops of H_2SO_4 and evaporated over a low flame to complete dryness. The small residue is finally blasted for a minute or two, cooled, and weighed. The difference between this weight and the weight previously obtained gives the amount of silica.*

Al_2O_3 and Fe_2O_3: The filtrate, about 250 c.c. from the second evaporation for SiO_2, is made alkaline with NH_4OH after adding HCl, if need be, to insure a total of 10 to 15 c.c. strong acid, and boiled to expel excess of NH_3, or until there is but a faint odor of it, and the precipitated iron and aluminum hydrates, after settling, are washed once by decantation and slightly on the filter. Setting aside the filtrate, the precipitate is dissolved in hot dilute HCl, the solution passing into the beaker in which the precipitation was made. The aluminum and iron are then precipitated by NH_4OH, boiled and the second precipitate collected and washed on the same filter used in the first instant. The filter-paper, with the precipitate, is then placed in a weighed platinum crucible, the paper burned off and the precipitate ignited and finally blasted 5 minutes, with care to prevent reduction, cooled and weighed as $Al_2O_3+Fe_2O_3$.†

Fe_2O_3: The combined iron and aluminum oxides are fused in a platinum crucible at a very low temperature with about 3 to 4 grams of $KHSO_4$, or, better, $NaHSO_4$, the metal taken up with so much dilute H_2SO_4 that there shall be no less than 5 grams absolute acid and enough water to effect solution on heating. The solution is then evaporated and eventually heated till acid fumes come off copiously. After cooling and redissolving in water the small amount of silica is filtered out, weighed, and corrected by HFl and H_2SO_4.‡ The filtrate is reduced by zinc, or preferably by hydrogen sulphide, boiling out the excess of the latter afterward while passing CO_2 through the flask, and tritrate

* For ordinary control work in the plant laboratory this correction may, perhaps, be neglected; the double evaporation never.

† This precipitate contains TiO_2, P_2O_5, Mn_3O_4.

‡ This correction of Al_2O_3, Fe_2O_3 for silica should not be made when the HFl correction of the main silica has been omitted, unless that silica was obtained by only one evaporation and filtration. After two evaporations and filtrations 1 to 2 mg. of SiO_2 are still to be found with the $Al_2O_3.Fe_2O_3$.

with permanganate.* The strength of the permanganate solution should not be greater than .0040 grain Fe_2O_3 per c.c.

CaO: To the combined filtrate from the $Al_2O_3+Fe_2O_3$ precipitate a few drops of NH_4OH are added, and the solution brought to boiling. To the boiling solution 20 c.c. of a saturated solution of ammonium oxalate is added, and the boiling continued until the precipitated CaC_2O_4 assumes a well-defined granular form. It is then allowed to stand for 20 minutes, or until the precipitate has settled, and then filtered and washed. The precipitate and filter are placed wet in a platinum crucible, and the paper burned off over a small flame of a Bunsen burner. It is then ignited, redissolved in HCl, and the solution made up to 100 c.c. with water. Ammonia is added in slight excess, and the liquid is boiled. If a small amount of Al_2O_3 separates, this is filtered out, weighed, and the amount added to that found in the first determination, when greater accuracy is desired. The lime is then reprecipitated by ammonium oxalate, allowed to stand until settled, filtered, and washed,† weighed as oxide by ignition and blasting in a covered crucible to constant weight, or determined with dilute standard permanganate.‡

MgO: The combined filtrates from the calcium precipitates are acidified with HCl, and concentrated on the steam-bath to about 150 c.c., 10 c.c. of saturated solution of $Na(NH_4)HPO_4$ are added, and the solution boiled for several minutes. It is then removed from the flame and cooled by placing the beaker in ice-water. After cooling, NH_4OH is added drop by drop with constant stirring until the crystalline ammonium magnesium orthophosphate begins to form, and then in moderate excess, the stirring being continued for several minutes. It is then set aside for several hours in a cool atmosphere and filtered. The precipitate is redissolved in hot dilute HCl, the solution made up to about 100 c.c., 1 c.c. of a saturated solution of $Na(NH_4)HPO_4$ added, and ammonia drop by drop, with constant stirring until the precipitate is again formed as described and the ammonia is in moderate excess. It is then allowed to stand for about 2 hours when it is filtered on a paper or a Gooch crucible, ignited, cooled, and weighed as $Mg_2P_2O_7$.

K_2O and Na_2O: For the determination of the alkalies, the well-known method of Prof. J. Lawrence Smith is to be followed, either with or without the addition of $CaCO_3$ with $NHCl_4$.

* In this way only is the influence of titanium to be avoided and a correct result obtained for iron.

† The volume of wash-water should not be too large, *vide* Hillebrand.

‡ The accuracy of this method admits of criticism, but its convenience and rapidity demand its insertion.

SO_3: One gram of the substance is dissolved in 15 c.c. of HCl, filtered and residue washed thoroughly.*

The solution is made up to 250 c.c. in a beaker and boiled. To the boiling solution 10 c.c. of a saturated solution of $BaCl_2$ is added slowly, drop by drop, from a pipette and the boiling continued until the precipitate is well formed, or digestion on the steam-bath may be substituted for the boiling. It is then set aside overnight, or for a few hours, filtered, ignited, and weighed as $BaSO_4$.

Total sulphur.—One gram of the material is weighed out in a large platinum crucible and fused with Na_2CO_3 and a little KNO_3, being careful to avoid contamination from sulphur in the gases from source of heat. This may be done by fitting the crucible in a hole in an asbestos board. The melt is treated in the crucible with boiling water and the liquid poured into a tall, narrow beaker, and more hot water added until the mass is disintegrated. The solution is then filtered. The filtrate contained in a No. 4 beaker is to be acidulated with HCl and made up to 250 c.c. with distilled water, boiled, the sulphur precipitated as $BaSO_4$ and allowed to stand overnight or for a few hours.

Loss on ignition.—Half a gram of cement is to be weighed out in a platinum crucible, placed in a hole in an asbestos board so that about three-fifths of the crucible projects below, and blasted 15 minutes, preferably with an inclined flame. The loss by weight, which is checked by a second blasting of 5 minutes, is the loss on ignition.

Note.—Recent investigations have shown that large errors in results are often due to the use of impure distilled water and reagents. The analyst should, therefore, test his distilled water by evaporation and his reagents by appropriate tests before proceeding with his work.

* Evaporation to dryness is unnecessary, unless gelatinous silica should have separated and should never be performed on a bath heated by gas, *vide* Hillebrand.

CHAPTER XXXVII.

PHYSICAL PROPERTIES: TESTING METHODS.

THE utilization of Portland cement does not properly come within the province of this volume, as it is already covered by several excellent books. An extensive and readily accessible literature has been created on the subject of testing methods and testing results; but most of this literature is more important to the professional cement-tester than to the cement-manufacturer or cement-user. In the present chapter the subject of testing will necessarily be considered, but merely incidentally. Stress will be laid, on the other hand, on the general properties which Portland cement develops in use, and attention will be directed to the chemical and physical agencies which tend to disintegrate, or weaken, or destroy the cement, or the structures in which it is used.

Physical Properties of Portland Cement.

Portland cement is at present used for many different purposes, and the use to which it is applied seems to be rapidly increasing. Under such circumstances it is necessary to supply a product well-fitted to withstand the various disintegrating agencies to which it may be subjected.

In its ordinary uses, in heavy masonry for example, the cement will be subjected to compressive stresses, but rarely to tensile. When used as a paving material it will encounter transverse stresses and severe abrasion. As a lining material its imperviousness will be tested. In other places, as in gun emplacements for example, it may be subjected to severe and often-repeated shocks.

To these physical agencies of disintegration or destruction, are added chemical agents, which are at times of paramount importance. Works exposed to sea-water, for example, are subject to purely chemical attack which must be guarded against so far as possible.

The situation might be summed up by stating that cement may fail through defects in its manufacture (internal agencies), or through

the purely external agencies, and that these agencies may be either physical or chemical.

This brief outline will serve to give some idea of the wide scope which might be given to a discussion of the properties of Portland cement.

Value of fineness tests.—The reason for testing the fineness of a cement depends on the facts that (*a*) the strength of the cement, and particularly its tensile strength when mixed with sand, increases with the fineness, and (*b*) the soundness of the cement may be improved by fine grinding. The second point is one that concerns the manu-

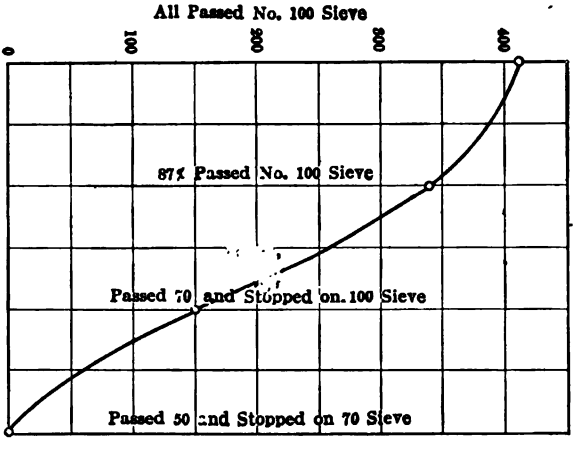

FIG. 133.*—Variation of tensile strength with fineness.

facturer more than the user, because an unsound cement will usually fail to pass other tests and will therefore be rejected.

The increase in strength consequent on increased fineness is well shown in Figs. 143 and 144, both showing the results of tests on 1 : 3 mixtures, the tests of Fig. 143 having been made at four months while those in Fig. 144 are at various ages.

The value of fine grinding is evident, and engineers are constantly raising the standard of fineness in specifications. Unfortunately, however, they fail to make proper use of this fine cement after they have paid extra for getting it. They insist, for example, in obtaining cement which will pass 92 or 95 per cent through a 100-mesh sieve, and then use it in the same sand mixtures that they would if it were an English cement passing perhaps 85 per cent through 100-mesh.

* From Johnson's "Materials of Construction," p. 409.

The actual fineness of a number of typical American Portlands is shown very exactly in the tests given in Table 223.

TABLE 223.

FINENESS OF VARIOUS AMERICAN PORTLANDS. (BLEININGER.)

Brand.	Reduced on.	Residue on 80-mesh Sieve.	Residue on 120-mesh Sieve.	Residue on 200-mesh Sieve.	Diameter between 0.008 and 0.002 Inch.	Diameter between 0.002 and 0.0002 Inch.	Diameter between 0.0003 and 0.0007 Inch.	Finer than Last Size.	Total Coarser than 200-mesh.
1	Tube mill.....	7.07	14.56	4.45	22.68	19.29	7.36	24.69	25.98
2	" "	9.01	15.35	5.09	21.50	20.53	7.06	21.52	29.45
3	" "	12.12	15.05	7.61	21.11	16.85	5.91	21.37	34.78
4	" "	14.11	14.57	7.82	22.43	13.95	7.81	19.32	36.49
5	" "	3.84	17.64	5.10	25.27	12.56	10.16	20.42	26.58
6	Griffin mill.....	3.06	15.41	8.24	28.56	16.48	12.74	15.51	26.72
7	" "	9.43	16.91	6.37	25.52	12.18	9.20	18.49	32.71
8	" "	5.00	15.42	14.52	27.30	19.10	9.22	14.88	29.53
9	" "	4.40	11.35	5.13	23.79	21.30	10.01	24.01	20.89
10	" "	4.18	13.30	5.07	22.63	14.64	12.31	28.79	22.55

Specific gravity.—The specific gravity of a Portland cement is a property which is of no importance of itself to the engineer. The

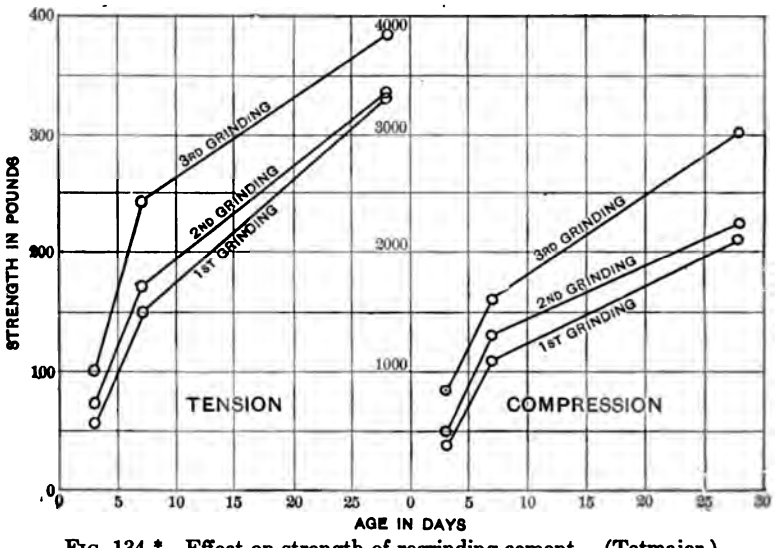

FIG. 134.*—Effect on strength of regrinding cement. (Tetmajer.)

reason for determining it is in order to rule out underburned or adulterated cement. The specific gravity of a well-dried sample of Port-

* From Johnson's "Materials of Construction," p. 411.

land cement will rarely fall below 3.10; while that of a natural cement, a slag cement, or a Portland adulterated with slag will rarely rise above 3.00. Some few American natural cements do, however, show a higher specific gravity, as can be seen from the table on page 254.

Setting properties.—A certain minimum time of initial and final set is usually specified, for the convenience of the workmen. This is regulated by the use of gypsum or plaster at the plant, a practice whose effects have been discussed in detail in Chapter XXXVI.

The effect of temperature on the setting of Portland cement is well shown in Fig. 135. It will be noted that the setting is much slower at low than at high temperatures, within the limits of the experiments.

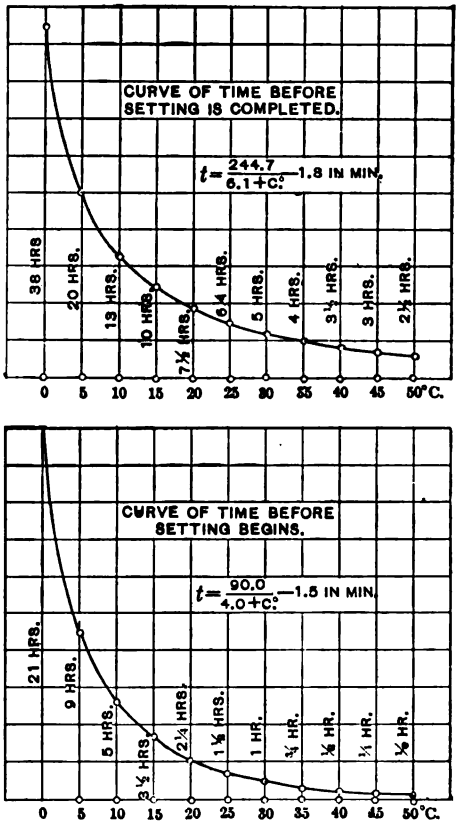

FIG. 135.*—Effect of temperature on setting time.

Tensile strength.—The tensile strength of a cement is of very little importance or interest of itself, because cements are rarely subjected *intentionally* to tensile strains. But in practice the tensile test is the most commonly applied of all tests, this action being based on the assumption that the ratio between compressive and tensile strength for all Portland cements is quite uniform, and that therefore variations in tensile strength will indicate corresponding (though much greater) variations in compressive strength. This assumption is to a large extent correct, and for all practical purposes may be considered satisfactory. The question as to the ratio existing between the two types of strength will be taken up on a later page (p. 533).

* From Johnson's "Materials of Construction," p. 616.

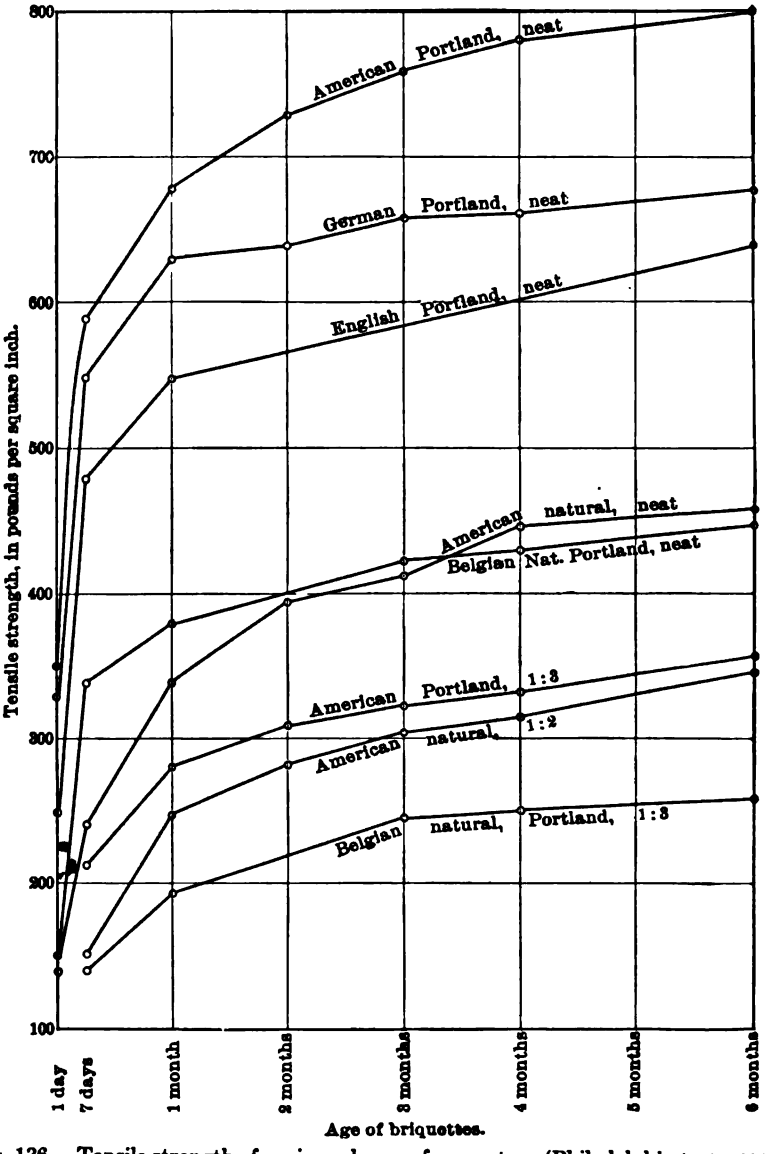

FIG. 136.—Tensile strength of various classes of cements. (Philadelphia tests, 1899.)

In Fig. 136 the results of a large series of tests on various classes of cement are shown diagrammatically. The cements tested included American and foreign Portlands, foreign "natural Portlands," and American natural cements, and the comparative results are quite representative.

The three points of most general interest in connection with tests of tensile strength are (*a*) the decrease in tensile strength with increase of percentage of sand, (*b*) the increase in strength with increased age, and (*c*) the variation in strength due to differences in the character

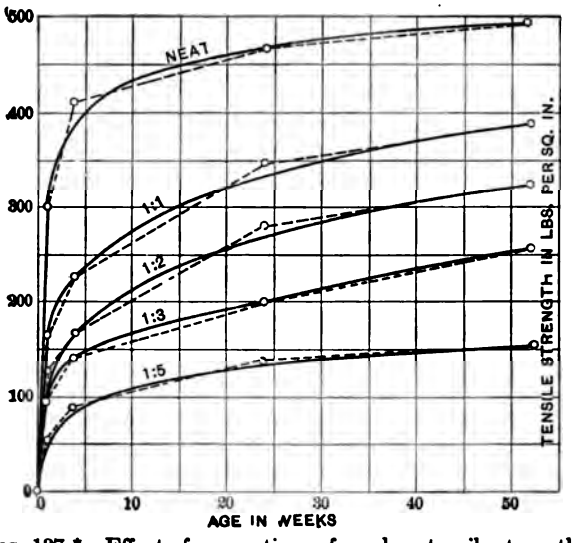

FIG. 137.*—Effect of proportions of sand on tensile strength.

of the sand. Two of these points are illustrated in Figs. 137 and 138, while all three are constantly discussed in engineering publications.

Compressive strength.—The compressive strength of a cement or concrete is a matter of direct practical importance, for these materials are rarely subjected to any other type of strain when used in actual work. Compressive tests, however, require the use of heavy testing machines, and are therefore not adapted for field or ordinary office tests. (See Tables 224 and 225.)

Ratio of compressive to tensile strength.—For a given age and mixture, the ratio between the compressive and tensile strength of a Portland-cement mortar is practically fixed. The ratio increases with increasing age, and also increases with increasing proportions of sand.

* From Johnson's "Materials of Construction," p. 571.

In Fig. 139 are plotted the curves, by Johnson, resulting from comparison of a large series of tests by Tetmajer on 1 : 3 mixtures.

TABLE 224.

COMPRESSIVE STRENGTH OF PORTLAND-CEMENT CUBES, WATERTOWN ARSENAL.

Brand.	Per Cent Water.	Compressive Strength Pounds per Square Inch.		
		7 Days.	1 Month.	3 Months.
Alpha	25	6010	7340	8580
Atlas	25	3490	5370	5870
Lehigh	26.8	4280	5590	6310
"	18	5780	5990	6980
Star, with plaster	22.5	5960	7080	8170
" " "	25	6320	6750	8180
" " "	30	6340	6850	7720
" without plaster	22.5	4620	5180	5930
" " "	25	5560	5980	7730
" " "	30	5030	5620	6810
Whitehall	25	5630	6640	7630
Alsen	29.2	3510	4940	5510
Josson	26.7	2750	4030	4660

Report on Tests of Metals, etc., at Watertown Arsenal, 1902, pp. 369–376.

TABLE 225.

COMPRESSIVE STRENGTH OF PORTLAND-CEMENT MORTAR AND CONCRETE CUBES, WATERTOWN ARSENAL.

Brand.	Composition			Age.			Size of Cube, Inches.	Compressive Strength per Square Inch.
	Cement.	Sand.	Stone.	Years.	Months.	Days.		
Atlas	1	1	..	2	5	20	6	11,330
" *	1	1½	..	2	5	19	6	10,390
" *	1	2	..	2	5	16	6	9,520
" *	1	2½	..	2	5	17	6	8,110
" *	1	3	..	2	5	15	6	6,140
" *	1	3½	..	2	5	13	6	6,280
" *	1	4	..	2	5	12	6	5,230
" *	1	2	4	..	..	7	12	1,303
" *	1	3	6	..	..	7	12	1,053
Alpha *	1	2	4	3	0	12	12	2,615
Vulcanite †	1	2	4	..	1	22	12	3,392
" †	1	2	4	..	2	25	12	4,135
Grant †	1	3	5	..	3	2	12	3,758

* Report on Tests of Metals, etc., at Watertown Arsenal, 1902, pp. 512–514.
† Ibid., 1900, pp. 1105–1111.

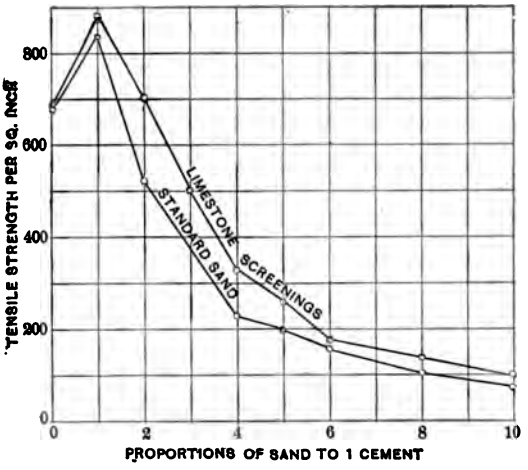

FIG. 138.*—Effect of character of sand on tensile strength.

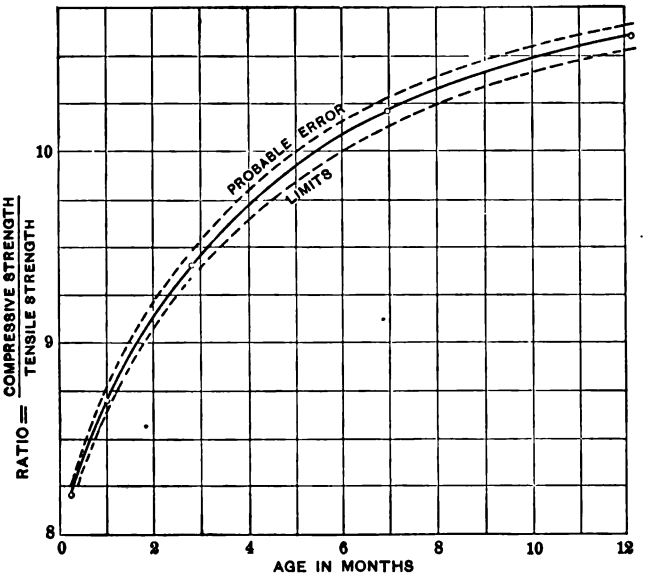

FIG. 139.†—Ratio of compressive to tensile strength. (Johnson.)

* From Johnson's "Materials of Construction," p. 581.
† From Johnson's "Materials of Construction," p. 419.

In practical use, it may be assumed that at the end of a year the average Portland-cement mortar will have a compressive strength about ten times as great as its tensile strength.

In Table 226 are given the results of a series of tests carried out at the Watertown Arsenal.* The tensile tests were made on the usual briquettes, the compressive tests on 2-inch cubes, and each average given is the result of ten tests. The cement used was the Peninsular brand, giving the following results for fineness and specific gravity:

Per cent of fineness:
- Retained on 98×100 sieve..... 4.95
- Passed by 98×100 sieve; retained on 174×182 bolting-cloth. 19.75
- Passed by 174×182 bolting-cloth..... 75.30

Specific gravity:
- As taken from barrel..... 3.20
- After mixing with 22 per cent water, setting 7 days in air, regrinding, and heating to a constant weight at 110° C.... 2.81

A chemical analysis of the cement is also given, but is evidently erroneous and therefore will not be quoted here.

TABLE 226.

RELATION OF TENSILE TO COMPRESSIVE STRENGTH. (WATERTOWN ARSENAL.)

Per Cent of Water.	Ages in		Tensile Strength, Pounds per Square Inch.			Compressive Strength, Pounds per Square Inch.		
	Air, Days.	Water, Days.	Maximum.	Minimum.	Average.	Maximum.	Minimum.	Average.
20	1	..	221	177	196	801	654	717
20	7	..	393	301	354	3430	2700	3040
20	28	..	641	487	566	4370	4940	3990
20	1	6	835	653	780	4830	3770	4250
20	1	27	952	857	906	8280	5730	7370
22	1	..	209	156	189	670	530	595
22	7	..	482	303	392	3680	3010	3260
22	28	..	518	421	457	4310	3030	3760
22	1	6	724	502	666	5370	3620	4720
22	1	27	1010	782	866	7810	5360	6870
25	1	..	223	148	190	450	398	430
25	7	..	475	301	402	3210	2120	2610
25	28	..	552	393	450	3550	2630	3130
25	1	6	388	251	329	4440	3360	3880
25	1	27	807	696	758	8740	6310	7580

* Report on Tests of Metals, etc., at Watertown Arsenal during 1902, p. 511. 1903.

Modulus of elasticity.—The determinations of the modulus of elasticity given in the following table were made at the Watertown Arsenal:

TABLE 227.

Brand.	Composition.	Weight per Cubic Foot, Pounds.	Age. Mos.	Age. Dys.	Ultimate Strength, Pounds per Square Inch.	*E*. Pounds per Square Inch.
Alpha.....	Neat	135.5	1	..	....	E(500–2000) = 3,000,000 E(500–3000) = 3,030,000
"	"	135.5	7	..	8530	E(500–2000) = 3,488,000 E(2000–4000) = 3,279,000 E(4000–6000) = 2,963,000
"	"	137.3	1	..	....	E(500–2000) = 3,061,000
"	"	137.3	5	..	9260	E(500–2000) = 4,545,000 (E2000–4000) = 4,255,000 E(4000–6000) = 3,846,000
Atlas.....	"	134.7	2½	..	....	E(500–2000) = 2,326,000
"	"	134.7	6½	..	5450	E(500–2000) = 2,479,000 E(2000–4000) = 2,581,000
Lehigh....	"	129.2	1	26	5800	E(500–2000) = 2,500,000 E(2000–4000) = 2,353,000
"	1 cement : 1 sand	133	1	26	3420	E(500–2000) = 2,778,000
"	Neat	135.9	1	26	7540	E(500–2000) = 4,348,000 E(2000–3000) = 4,444,000
Peninsular.	"	135.3	2	13	6710	E(500–2000) = 3,571,000 E(2000–3000) = 3,448,000 E(3000–4000) = 3,125,000
"	"	138.0	2	14	6720	E(500–2000) = 3,846,000 E(2000–3000) = 3,571,000 E(3000–4000) = 3,509,000
"	1 cement : 1 sand	133.4	2	13	4200	E(500–2000) = 2,941,000 E(2000–3000) = 2,439,000

Sand cement.—Sand cement, or silica cement, is the name given to the product made by grinding up together Portland cement with an equal or greater quantity of sand, limestone, or other chemically inert substance. Description of the making and properties of sand cement is not properly part of a discussion of the manufacture of Portland cement, but rather a matter for the engineer to consider in connection with the uses of cement. For this reason the question will be touched on very briefly.

It is found that if Portland cement be mixed with an equal quantity of sand or limestone and the mixture ground very finely in a tube mill, the resulting product (sand cement) will show a strength almost or quite as great as the Portland cement from which it was made, notwithstanding the fact that the sand cement consists only half of Port-

land cement. When Portland cement is very expensive, economies are, therefore, possible in this line.

The gain in strength is due entirely to the extra fineness given by the extra grinding. The sand does not enter into chemical combina-

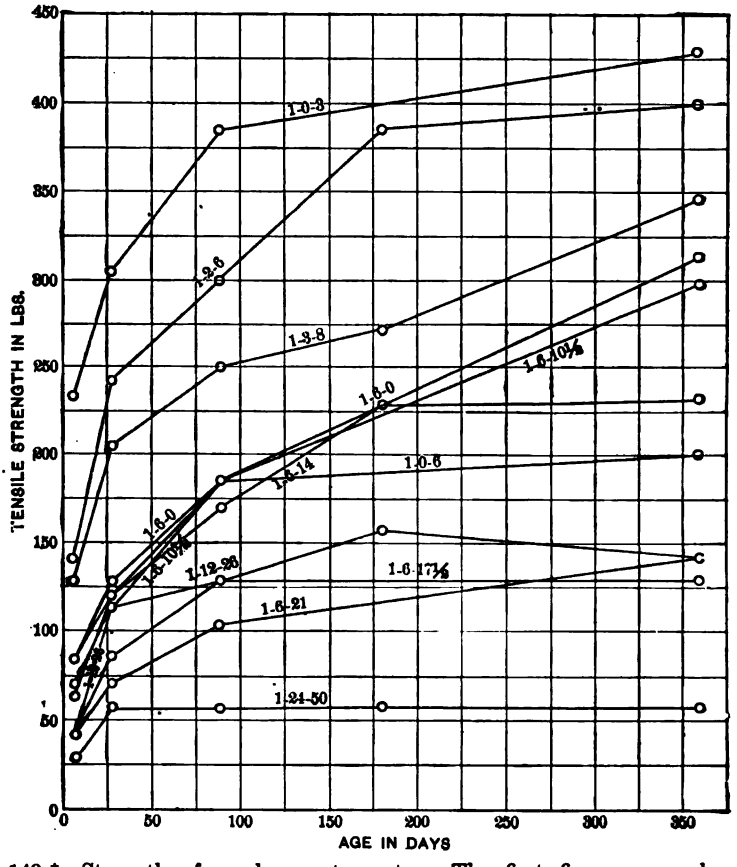

FIG. 140.*—Strength of sand-cement mortar. The first figure on each curve denotes parts of Portland cement; the second, parts of ground sand; the third, parts of unground sand.

tion with the cement in any way, for ground limestone will give as good results as ground quartz.

The tests quoted in Table 228 were made at Albany in the laboratory of the State Engineer. Iron Clad is a Portland cement of high

* From Johnson's "Materials of Construction," p. 579.

grade, while Victor was the sand cement made from it by grinding Iron Clad with limestone.

TABLE 228.

COMPARATIVE TESTS OF PORTLAND CEMENT AND SAND CEMENT.

	Cement.	Fineness.		Setting-time, Minutes.		Tensile Strength, Pounds.	
		50-mesh.	100-mesh.	Initial.	Final.	7 Days.	28 Days.
1897.	Iron Clad, 1 : 3.....	100	94¾	51	122	170	274
	Victor, 1 : 3.....	100	96	35	79	198	265
1898.	Iron Clad, 1 : 3.....	99⅞	94¼	27	81	189	277
	Victor, 1 : 3.....	100	96	41	89	184	272
1899.	Iron Clad, 1 : 3.....	100	98	45	94	207	311
	Victor 1 : 3.....	100	100	60	158	178	264

TABLE 229.

TENSILE AND COMPRESSIVE STRENGTH OF SAND CEMENTS. (SMITH.)

Name of brand.....	Citadel	Ensign	Jubilee
Sand cement composed of.....	1 cement 1 sand	1 cement 1 sand	1 cement 6 sand
Fineness: Passing 100-mesh.....	99.8	99.4	99.7
" 120- "	....	99.3	98.4
" 180- "	99.3		
Neat sand cement: Tension, 1 week.....	332		
" 4 weeks.....	475		
" 4 months.....	....	810	340
" 6 "	....	780	540
Compression, 4 weeks.....	3837		
Sand cement 1, sand 1: Tension 1 week.....	....	....	300
" 2 weeks.....	....	....	379
Compression, 1 week..	....	....	2800
Sand cement 1, sand 2: Tension 1 week.....	....	....	184
" 2 weeks.....	....	....	215
Compression, 1 week..	....	....	1225
Sand cement 1, sand 3: Tension, 1 week.....	135	189	
" 2 weeks.....	....	201	
" 4 "	141		
" 2 months....	135		
Compression, 1 week..	470	900	
" 4 weeks..	687		

Brickbuilder, vol. 6, p. 281.

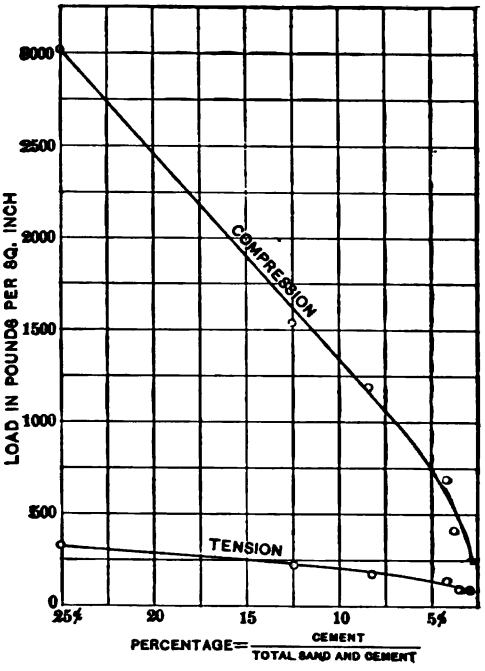

FIG. 141.*—Strength of sand-cement mortar with varying proportions of sand.

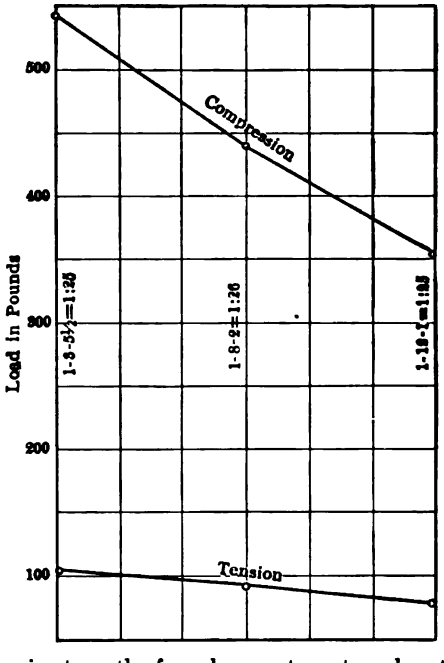

FIG. 142.†—Variation in strength of sand-cement mortar when the total proportion of sand is constant, but the relative proportions of ground and unground sand are variable.

* From Johnson's "Materials of Construction," p. 580. † Ibid., p. 581.

TABLE 230.

COMPRESSIVE STRENGTH OF SILICA-CEMENT CUBES. (WATERTOWN ARSENAL.)

Per Cent Water.	Age.	Dimensions of Cube.			Compressive Strength.		
		Height, Inches.	Surface, Inches.	Compressed Area, Square Inches.	Total Pounds.	Per Square Inch, Pounds.	Average Pounds per Square Inch.
28½	7 days	4.05	4.00×4.06	16.24	19,950	1228	
28½	"	4.00	4.09×4.08	16.68	22,600	1355	
28½	"	4.03	3.98×4.13	16.44	20,900	1271	1300
28½	"	3.96	4 03×4.07	16.40	19,980	1218	
28½	"	3.96	4.06×4.10	16.64	23,500	1412	
28½	1 month	3.96	4.15×4.04	16.77	27,100	1616	
28½	"	3.97	4.02×4.18	16.80	30,600	1821	
28½	"	3.96	4.04×4.07	16.44	33,500	2038	1790
28½	"	3.98	4.04×4.06	16.40	27,900	1701	
28½	"	4.00	4.13×4.00	16.69	29,500	1768	
28½	3 months	3.97	4.01×4.10	16.44	32,800	1995	
28½	"	3.99	4.05×4.05	16.40	34,100	2079	
28½	"	3.96	4.08×4.09	16.69	34,500	2067	2110
28½	"	3.98	4.01×4.18	16.76	29,200	2339	
28½	"	3.96	4.05×4.10	16.61	34,500	2077	
28½	12 months	3.96	4.03×4.19	16.89	33,600	1990	2190
28½	"	3.98	4.07×4.10	16.69	39,900	2390	
18	8 days	4.00	3.92×4.13	16.19	47,100	2910	
18	"	4.06	3.99×4.00	15.96	53,100	3330	
18	"	4.08	4.00×3.95	15.80	53,400	3380	3050
18	"	4.02	4.06×3.86	15.67	43,600	2780	
18	"	3.99	3.98×4.08	16.24	46,500	2860	
18	1 month	4.00	4.03×3.98	16.04	54,900	3420	
18	"	4.00	4.02×4.08	16.40	60,600	3700	
18	"	4.08	4.01×4.00	16.04	65,800	4100	3470
18	"	4 05	4.01×3.98	15.96	39,500	2480	
18	"	4.07	4.00×4.06	16.24	59,400	3660	
18	3 months	4.08	3.98×4.05	16.12	76,100	4720	
18	"	4.00	4.09×4.03	16.48	70,500	4280	4470
18	"	4.08	4.00×4.02	16.08	73,600	4580	
18	"	3.98	4.05×4.06	16.44	70,600	4290	

Report of Tests of Metals, etc., at Watertown Arsenal for 1902, pp. 376–377. 1903.

List of references on sand cement.—The following papers are of interest in this connection:

Butler, M. J. Silica Portland cement. Canadian Engineer, March, 1899.

Klein, O. H. Report on concrete foundations for pavements. 8vo, 58 pp. New York, 1903. (Much criticism of sand cements.)

Reeves, H. E. The effect of grinding mixed sand and cement. Technograph, May, 1896.

Smith, C. B. Sand cement. Brickbuilder, vol. 6, p. 280. 1897. (Tests of three Canadian brands. Important paper.)

TABLE 231.

COMPRESSIVE STRENGTH OF SAND-CEMENT MORTARS. (WATERTOWN ARSENAL.)

Brand.	Composition.	Age.		Average Strength, Pounds per Square Inch.	
		Months.	Days.	In Air.	In Water.
Silica	Neat	..	7	1670	1880
"	"	1	..	2070	2830
"	"	3	..	2420	3110
"	1 cement, 1 sand	..	6	942	1090
"	" "	1	..	1460	1920
"	" "	3	..	1610	2340
"	1 cement, 2 sand	..	5	386	424
"	" "	1	..	424	708
"	" "	3	..	850	1120
"	1 cement, 3 sand	..	4	130	132
"	" "	1	..	219	360
"	" "	3	..	306	571

Report of Tests of Metals, etc., at Watertown Arsenal, 1902, p. 443.

TABLE 232.

MODULUS OF ELASTICITY OF SAND CEMENT. (WATERTOWN ARSENAL.)

Brand.	Mortar.	Weight per Cu. Ft. Pounds.	Time. Mos.	Time. Dys.	Ultimate Strength.	*E*. Pounds per Square Inch.
Silica	Neat	117.8	1	28	2520	E(100–1000) = 1,607,000 E(1000–2000) = 1,205,000
"	"	116.3	1	28	2400	E(100–1000) = 1,475,000 E(1000–2000) = 1,117,000
"	1 cement, 1 sand	126.9	1	29	1200	E(100–1000) = 1,286,000
"	1 cement, 2 sand	122.4	1	28	618	E(100–500) = 909,000
"	1 cement, 3 sand	120.8	1	27	404	E(100–400) = 632,000

Report of Tests of Metals, etc., at Watertown Arsenal, 1902, pp. 498–500.

References on sand cement—(*Continued*).

Anon. The manufacture and use of sand cement. Engineering News, April 16, 1896.

Anon. Le Silico-Portland on silico-cement. La Revue Technologique, Jan. 25, 1898.

Anon. The hydraulic experiment station of Cornell University. Engineering News, vol. 41, pp. 130–133. March 2, 1899. (Description of use of sand cement.)

Effect of heating.—The effect of high temperatures on cements or concretes is, in these days of fireproof construction, a matter of con-

siderable interest to architects and engineers. In 1902 a series of tests along this line were carried out at Watertown Arsenal, some of which are summarized in Table 219, below.

These tests were made on 2-inch cubes of neat Portland cement, all being crushed at a period of 1 year, 1 month, and 16 days after making.

"The cubes for this series were prepared and set in air or in water for a period of one year to a year and a half before they were heated, and intervals ranging from four days to nearly four months intervened between the time of heating and the time of testing.

"The heated cubes were gradually raised to the temperatures recorded, and slowly cooled in dry sawdust or powdered asbestos. The time of heating was one hour, and the maximum temperature was maintained for one hour.

"Cubes which were set in water were dried off on a radiator for twenty-four hours before heating in the muffle to the temperatures recorded.

"During heating some of the cubes developed fine cracks, at first faintly shown, which enlarged after a few hours or days had elapsed. In other cases the cracks appeared more promptly. Among those which were heated to the higher temperatures of the series, which ranged from 200° to 1000° F., there were cubes so badly cracked as to be unsuitable for testing."

TABLE 233.

EFFECT OF HEATING ON COMPRESSIVE STRENGTH. (WATERTOWN ARSENAL.)

Brand.	Per Cent Water.	Heated to.	Compressive Strength, Pounds per Square Inch.
Alpha	25	not heated	9167
"	25	200° F.	8830
"	25	300° F.	7920
"	25	400° F.	9190
"	25	500° F.	9400
"	25	600° F.	9000
"	25	700° F.	8217
"	25	800° F.	8730
"	25	900° F.	6060
Dyckerhoff	29	not heated	5017
"	29	600° F.	4347
"	29	700° F.	3483
"	29	800° F.	4280

Report of Tests of Metals, etc., at Watertown Arsenal, 1902, pp. 459–460.

Effects of salt and freezing.—The use of cement or concrete in buildings constructed during very cold weather has led to a long series of

experiments, designed to determine the effects of using salt and other anti-freezing agents in the water used in mixing the mortar.

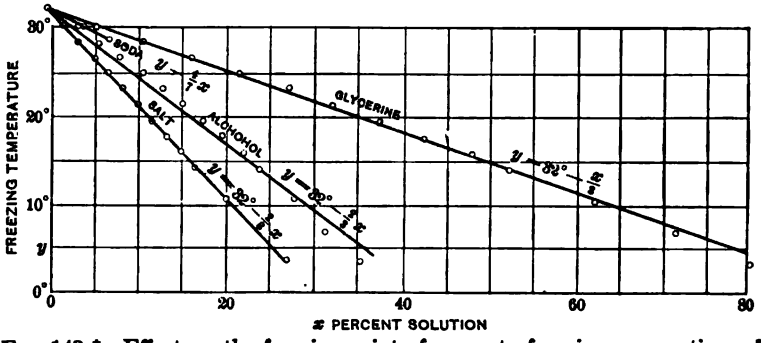

FIG. 143.*—Effect on the freezing-point of cement of various proportions of glycerine, alcohol and salt. (Tetmajer.)

The results of a number of such tests are shown diagrammatically in Figs. 143 to 148, inclusive. The results as to strength are rather con-

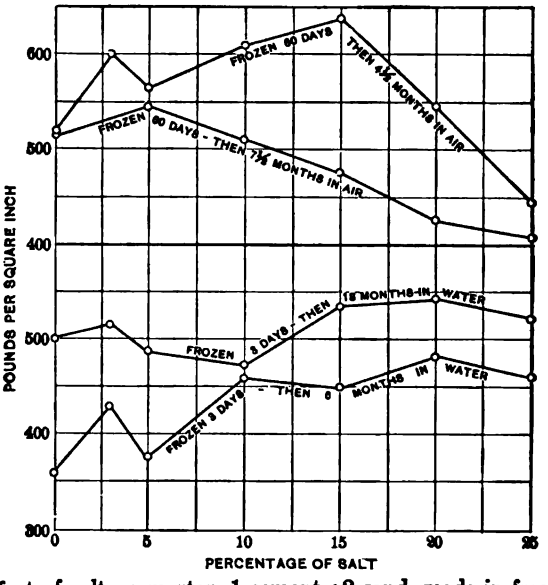

FIG. 144.†—Effect of salt on mortar, 1 cement : 2 sand, made in freezing weather. (Sabin.)

tradictory, but it seems probable that any addition of salt will decrease the ultimate tensile and compressive strength of the mortar in which

* From Johnson's "Materials of Construction," p. 615. † Ibid., p. 617.

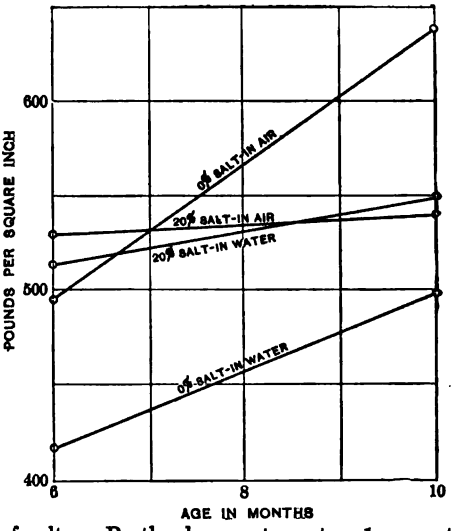

FIG. 145.*—Effect of salt on Portland-cement mortar, 1 cement : 2 sand, made in freezing weather. (Sabin.)

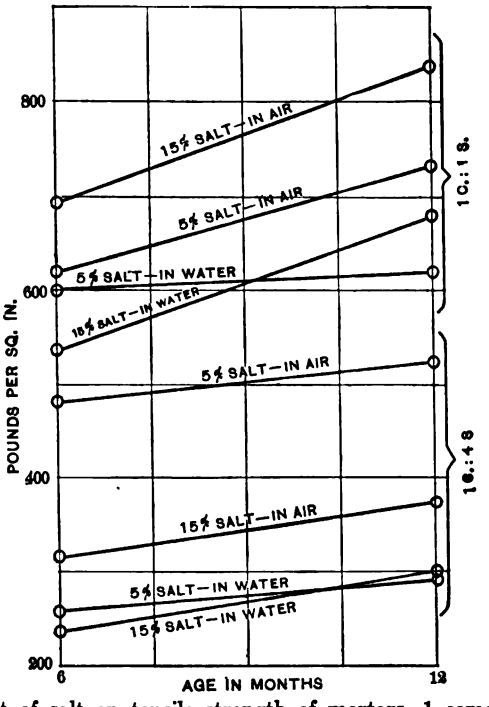

FIG. 146.†—Effect of salt on tensile strength of mortars, 1 cement ; 1 sand and 1 cement : 4 sand. Those left in air remained frozen almost sixty days. Those put in water were first frozen in air for three days.

* From Johnson's "Materials of Construction," p. 618. † Ibid., p. 619.

it is used, but that for the lower percentages of salt this injurious effect may be slight enough to be safely disregarded.

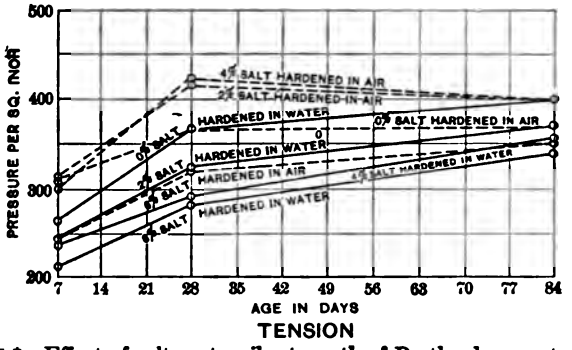

FIG. 147.*—Effect of salt on tensile strength of Portland-cement mortar. (Tetmajer.)

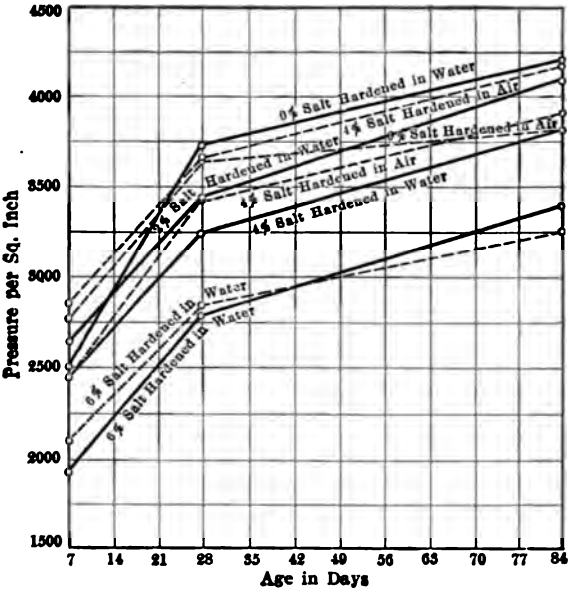

FIG. 148.†—Effect of salt on compressive strength of Portland-cement mortar. (Tetmajer.)

Effects of exposure to sea-water.—Portland cement is not entirely satisfactory in its resistance to exposure to salt water, though in part

* From Johnson's "Materials of Construction," p. 620. † Ibid.

this is often due to the use of porous mixtures which permit access of the water to the interior of the block of cement or concrete. The use of richer mixtures, or at least of a richer mixture for the surface of the block, will do away with many of the difficulties encountered. Aside from this, two methods of improvements have been advocated. One is to make the cement more resistant of itself by making it of such a chemical composition as will show the maximum resistance to the effects of salt water. This is the method of Le Chatelier, discussed below. The second method is, to add to the cement, trass, slag, or other puzzolanic material, in order that the lime liberated by the cement during hardening may be taken up and combined with the trass.

Le Chatelier considers that the aluminous compounds present in Portland cement are the direct cause of its destruction by sea-water. His theory, to account for this disintegration, is as follows: Free lime, liberated during the hardening of the cement, reacts with the magnesium sulphate always present in sea-water, to form calcium sulphate. This in turn reacts with the calcium aluminate of the cement to form a sulphaluminate of lime, which swells considerably on hydration and thus disintegrates the cement mass. The extent of the disintegration varies directly with the percentage of alumina present in the cement. Cements containing 1 or 2 per cent of alumina are, for example, practically unaffected by sea-water; while in cement containing as high as 7 or 8 per cent of alumina the swelling and consequent disintegration are very rapid.

If the alumina of a cement be replaced by an oxide not reacting with calcium sulphate, the stability of the cement in sea-water is greatly improved. Le Chatelier has demonstrated this by preparing cements in which the alumina was replaced by oxides of iron, chromium, cobalt, etc. All of these were more resistant than an alumina cement to the disintegrating effect of lime sulphate. The best effects were obtained when iron oxide was used, a cement corresponding in composition to $5SiO_2,Fe_2O_3,17CaO$ being found to be not only stable in presence of sea-water, but to possess excellent mechanical properties.

Deval's researches * on the effect of direct addition of calcium sulphate to various cements confirm the above theory. Each of the finely ground cements tested was completely hydrated by mixing with 50 per cent of water, and storing the mixture under water for three months out of contact with carbon dioxide. The mass was then dried, reground, mixed with half its weight of calcium sulphate and 33 per cent of water, and made up into rods, which were kept moist and protected from carbon

* Abstract in Journ. Soc. Chem. Industry, vol. 21, pp. 971–972.

dioxide by storage on moistened filter paper under a glass bell. At the end of three weeks the increase in length of the rods was measured, with the following results:

TABLE 234.

EFFECT OF ALUMINA.

Type of Cement.	Per Cent of Alumina in the Cement.	Per Cent of Elongation of the Rods.
Slag cement (Vitry)	15.5	27
Slag cement (Champignolles)	14.5	16
Grappier cement (Besses)	7.5	14
Portland cement	6.2	12
Hydraulic lime (Besses)	4.7	4

It will be noted that the percentage of elongation of the rods, varied directly with the percentage of alumina in the cements tested, proving conclusively that the welling was due to the action of the calcium sulphaluminate formed during the operation.

The work of Candlot, on the other hand, suggests that alumina *per se* is not an injurious ingredient for sea-water cements; and that immunity from marine action may in fact be effectively gained by increasing the normal alumina content. As a laboratory problem the matter is still unsettled, but meantime the results attained during five years or more of actual use by the high-alumina *ciment fondu* have conclusively supported Candlot's views.

Resistance to shock.—At the time the first edition of this book was published, some German experiments, the French test on forts, and the Japanese experiences at Port Arthur were all that threw light on the subject of concrete resistance under direct and repeated shock. Since then the matter has been tested on an enormous scale. For a summary of the results reference may be made to the papers cited below.* Here it may be said only that the resistance of concrete to shell shock seems to have depended less upon the character and quality of the cement employed than upon the proportions of the mix, the thickness of the mass, and the presence or absence of reinforcing.

At various points on the western front concretes of hydraulic lime, slag cement, normal Portland cement and high-alumina cement were employed. Of these the first two had the serious disadvantages of being slow-hardening; otherwise their resistance was fair enough. Unrein-

* Eckel, E. C. Concrete in front-line work, 1914–1917. Concrete, vol. 20, pp. 173–176, 199–200, 222–223, 1922.

forced concrete, even of good materials, tended to fall apart under continued shock, particularly when the proportioning gave an overload of coarse material—pebbles or stone. Reinforcing helped materially to reduce damage. The chief lesson of the whole matter was that refined laboratory methods of proportioning and designing led frequently to failure in actual practice, because actual work in the field is not at all refined.

Effects of storage.—Cement when stored under ordinary conditions shows rather heavy decreases in strength, along with slowing of its setting time. These results have been determined by Abrams * in a series of tests under varying storage conditions.

As to the *extent* of the deterioration Abrams found that cement stored in sacks in an outdoor shed had strengths as follows:

After 3 months storage, 80 per cent of original strength
After 6 months storage, 71 per cent of original strength
After 12 months storage, 61 per cent of original strength
After 24 months storage, 40 per cent of original strength

As to the *form* of the deterioration, it resulted in all cases in a greater loss of strength in short-time tests than in long-time tests; and in all cases it caused slowing of both initial and final setting times.

Standard Cement Testing Methods, U. S. A.

Beginning in 1903, and lasting on until the present day, various American technical societies and government departments have been working on cement testing methods and cement specifications. At various dates during that period preliminary and final reports on different phases of the work have been issued by the Society of Chemical Industry, the American Society of Civil Engineers, the American Society for Testing Materials, and the U. S. Bureau of Standards. The resulting specifications, in so far as they are purely specifications, will be found on pages 569 to 574 of this volume; the detailed methods of chemical analysis on pages 524 to 527. In the present chapter the methods adopted for the physical tests will be summarized.

Specific gravity.—The Le Chatelier specific gravity flask is officially adopted as the standard apparatus for this test, but the test itself is falling into disfavor.

* Abrams, Duff A. Effect of storage of cement. Bulletin 6, Structural Materials Laboratory, Lewis Institute, Chicago, 8vo, pp. 29, 1920.

The flask (Fig. 149) is filled with kerosene free from water, or with benzine not lighter than 62° Baumé, to a point on the stem between zero and 1 c.c. 64 grams of cement, of the same temperature as the liquid, is slowly introduced, taking care that the cement does not adhere to the inside of the flask above the liquid, and to free the cement from air by rolling the flask in an inclined position. After all the cement is introduced the level of the liquid will have risen to some division of the graduated neck; the difference between this and the original reading is the volume displaced by 64 gr. cement. The specific gravity then equals the weight of cement divided by the displaced volume.

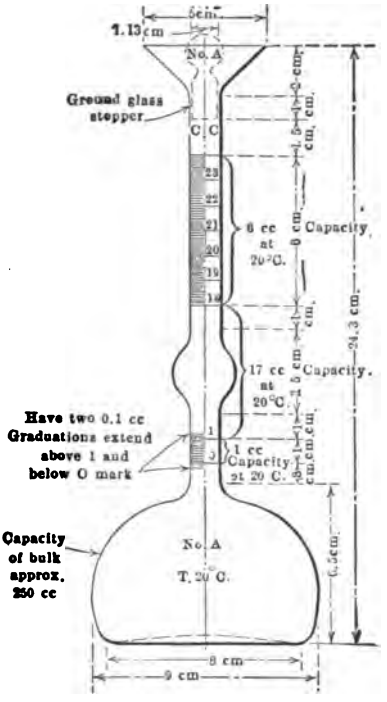

FIG. 149.—Le Chatelier specific gravity flask.

Fineness.—The apparatus used for fineness tests is a standardized No. 200 sieve. This has nominally 200 wires to the linear inch; is circular, approximately 8 inches in diameter; with wires woven from brass or bronze usually. The wire should be 0.0021 inch in diameter, giving nominally an opening of 0.0029 inch.

"The test shall be made with 50 gr. cement. The sieve shall be thoroughly clean and dry. The cement shall be placed on the sieve, with pan and cover attached, if desired, and shall be held in one hand in a slightly inclined position so that the sample will be well distributed over the sieve, at the same time gently striking the side about 150 times per minute against the palm of the other hand on the up stroke. The sieve shall be turned every 25 strokes about one-sixth revolution in the same direction. The operation shall continue until not more than 0.05 gram passes through in one minute of continuous sieving."

Normal consistency.—The Vicat apparatus is adopted as standard. It consists of a frame *A* (Fig. 150) bearing a movable rod *B*, weighing 300 grams, one end *C* being 1 cm. in diameter for a distance of 6 cm.; the other having a removable needle *D*, 1 mm. in diameter and 6 cm. long.

The rod is reversible, and can be held in any desired position by a screw *E*, and has midway between the ends a mark *F* which moves under a scale (graduated in millimeters) attached to the frame *A*. The paste is held in a conical hard-rubber ring *G*, 7 cm. in diameter at the base, 4 cm. high, resting on a glass plate *H* about 10 cm. square.

In making the determination, 500 gr. of cement, with a measured quantity of water, shall be kneaded into a paste, as described in section 37, and quickly formed into a ball with the hands, completing the operation by tossing it six times from one hand to the other, maintained about 6 inches apart; the ball resting in the palm of one hand shall be

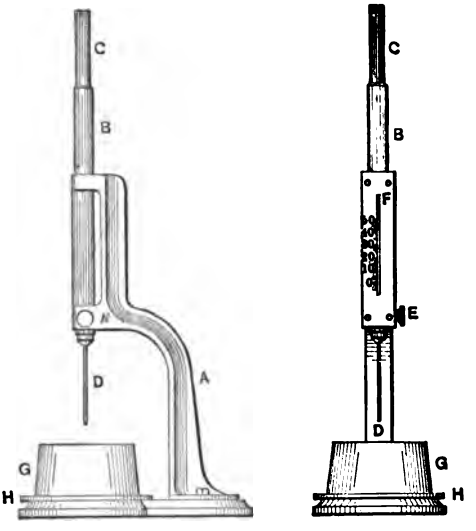

FIG. 150.—Vicat apparatus for testing consistency.

pressed into the larger end of the rubber ring held in the other hand, completely filling the ring with paste; the excess at the larger end shall then be removed by a single movement of the palm of the hand; the ring shall then be placed on its larger end on a glass plate and the excess paste at the smaller end sliced off at the top of the ring by a single oblique stroke of a trowel held at a slight angle with the top of the ring. During these operations care shall be taken not to compress the paste. The paste confined in the ring, resting on the plate, shall be placed under the rod, the larger end of which shall be brought in contact with the surface of the paste; the scale shall be then read, and the rod quickly released. The paste shall be of normal consistency when the

rod settles to a point 10 mm. below the original surface in one-half minute after being released."

Trial pastes shall be made with varying percentages of water until the normal consistency is obtained. The amount of water required shall be expressed in percentage by weight of the dry cement. Having determined the normal consistency of the cement, the amount of water required for the mortar briquettes is found from the following table, the values stated being in percentages of cement plus sand:

Percentage of Water for Neat Cement Paste of Normal Consistency.	Percentage of Water for One Cement, Three Standard Ottawa Sand.	Percentage of Water for Neat Cement Paste of Normal Consistency.	Percentage of Water for One Cement, Three Standard Ottawa Sand.
15	9.0	23	10.3
16	9.2	24	10.5
17	9.3	25	10.7
18	9.5	26	10.8
19	9.7	27	11.0
20	9.8	28	11.2
21	10.0	29	11.3
22	10.2	30	11.5

Soundness.—The method adopted to determine soundness is unfortunately not quantitative; in the course of time it will probably be replaced by the use of Vicat needles or some other modern and exact device. As now adopted the American method involves the use of any steam apparatus which can maintain the test pieces at temperatures between 98° and 100° C.

A pat from cement paste of normal consistency about 3 inches in diameter, one-half inch thick at the center, and tapering to a thin edge, shall be made on clean glass plates about 4 inches square, and stored in moist air for 24 hours. In molding the pat the cement paste shall first be flattened on the glass and the pat then formed by drawing the trowel from the outer edge toward the center.

The pat shall then be placed in an atmosphere of steam at a temperature between 98° and 100° C. upon a suitable support 1 inch above boiling water for five hours.

Should the pat leave the plate, distortion may be detected best with a straight edge applied to the surface which was in contact with the plate.

Setting time.—The Vicat apparatus used for determining consistency is also adopted for setting time determinations.

A paste of normal consistency is molded in the hard-rubber ring, and placed under the rod (*B*), the smaller end of which is then carefully brought in contact with the surface of the paste, and the rod quickly released.

The initial set is said to have occurred when the needle ceases to pass a point 5 mm. above the glass plate; and the final set, when the needle does not sink visibly into the paste.

The test pieces should be kept in moist air during the test; this may be accomplished by placing them on a rack over water contained in a pan and covered by a damp cloth; the cloth to be kept from contact with them by means of a wire screen; or they may be stored in a moist box or closet.

Care should be taken to keep the needle clean, as the collection of cement on the sides of the needle retards the penetration, while cement on the point may increase the penetration.

The time of setting is affected not only by the percentage and temperature of the water used and the amount of kneading the paste receives, but by the temperature and humidity of the air, and its determination is, therefore, only approximate.

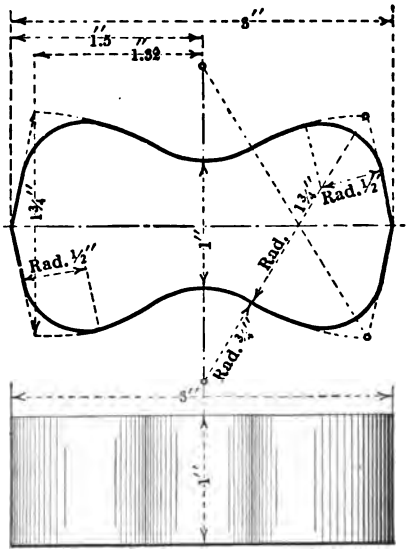

FIG. 151.—Standard American cement briquette.

Standard sand.—The sand adopted as the American standard is "natural sand from Ottawa, Illinois, screened to pass a No. 20 sieve and retained on a No. 30 sieve. This sand having passed the No. 20 sieve shall be considered standard when not more than 5 gr. pass the No. 30 sieve after one minute continuous sieving of a 500 gr. sample."

It may be noted in passing that though it may be convenient to describe the sand from the Ottawa locality as a " natural sand," it is not entirely exact. The sand there quarried is the residuum from the decay of a loosely cemented sandstone.

Standard test-pieces.—The briquette adopted as standard in the United States has the form and dimensions noted in Fig. 151. The briquettes are to be hand-molded, without mechanical compression; in testing the load is to be applied at the rate of 600 pounds per minute.

CHAPTER XXXVIII.

SPECIFICATIONS FOR PORTLAND CEMENT.

VARIOUS specifications for Portland cement have been collected for insertion in the present chapter. These are of interest partly for comparison and partly to show the growth of intelligent treatment of this subject.

Since the first edition of this book was published progress in the direction of standardization has been very rapid, and we have now reached essential uniformity in this regard. The result of such uniformity, here as elsewhere in American industry, is the production of large tonnages of product, all of essentially the same type and grade. To this extent standardization is an advantage; in its broader effects on the future development of better cements it may not be helpful.

New York State Canals, 1896.

The mortar and grout will be made of the best quality of Portland or natural hydraulic cement, as may be directed, and clean, sharp sand, in such proportions and made and used in such manner as may be required by the engineer.

No cement shall be used in any part of the masonry until the State engineer shall have examined, tried, and approved the same. It must be delivered in tight casks or bags, as the division or resident engineer may direct, and thereafter be properly protected from the weather.

The engineer to direct in what manner the sand shall be screened and worked, and washed, if necessary. When considered necessary by the engineer, salt shall be used with the mortar in such manner and proportions as he may direct.

Special directions shall be given by the engineer as to the delivery of cement and as to the time and facilities required for testing it previous to its use in the work. No cement will be used except in compliance with these directions. All facilities required by the engineer for securing tests must be afforded by the contractor. All cement must be stored in substantial water-proof structures from the time of delivery till used.

All cement offered for use in any work will be sampled by an agent of the State Engineer's Department. Samples will be collected immediately on delivery of cement at site of work, and contractors will promptly notify the engineer of the receipt of cement, in order that no delay may be had in the sampling thereof. All samples will be forwarded to the cement-testing office in Albany, and will be subjected to the following tests, and any cement failing on either of them will be rejected, though the further right is reserved to reject any and all cements the qualities of which have not become well known through prior use in State work or elsewhere.

Portland cement must be of the best quality and of such fineness that 95 per cent of the cement will pass through a sieve of 2500 meshes to the square inch, and 90 per cent through a sieve of 10,000 meshes per square inch. Portland cement when mixed neat and exposed one day in air and six days in water shall withstand a tensile strain of not less than 400 lbs. to the square inch, and when mixed in the ratio of 3 lbs. clean, sharp sand to 1 lb. of cement and exposed one day in air and six days in water, it shall withstand a tensile strain of not less than 125 lbs. per square inch.

Rapid-transit Subway, New York City, 1900-1901.

Fineness.—Ninety-eight per cent shall pass a No. 50 sieve and 90 per cent a No. 100 sieve.

Tensile strength.—At the end of one day in water after hard set, 150 lbs. neat; at the end of seven days, one day in air, six days in water, 400 lbs. neat; at the end of twenty-eight days, one day in air, twenty-seven days in water, 500 lbs. neat. When mixed 2 to 1 with quartz sand: At the end of seven days, one day in air, six days in water, 200 lbs.; at the end of twenty-eight days, one day in air, twenty-seven days in water, 300 lbs.

Chemical analyses.—Chemical analyses will be made from time to time, and cement furnished must show a reasonable uniform composition.

Soundness.—Tests for checking and cracking and for color will be made by molding, on plates of glass, cakes of neat cement about 3 inches in diameter, ½ inch thick in the center, and with very thin edges. One of these cakes when set perfectly hard shall be put in water and examined for distortion or cracks, and one shall be kept in air and examined for color, distortion, and cracks. Another cake shall be allowed to set in steam for twenty-four hours and then put in boiling water for

twenty-four hours. Another cake shall be allowed to set hard in dry air for twenty-four hours and then put in boiling water for twenty-four hours. Such cakes should at the end of the tests still adhere to the glass and show neither cracks nor distortion. A briquette, in like manner, should be allowed to set hard in dry air for twenty-four hours, then boiled for twenty-four hours, be kept for five days in water, and show 350 lbs. tensile strength.

Department of Bridges, New York City, 1901.

(106) That all cement used on this work must be the best quality of imported or American Portland cement, manufactured by works of established reputation for furnishing a high-grade and uniform product. Cement must show a chemical analysis satisfactory to the engineer.

(107) That briquettes of neat cement exposed to air for twenty-four hours and then immersed in water for six days must have a tensile strength of at least 400 lbs. per square inch.

(108) That briquettes of mortar mixed in proportion of one part of cement to two and one-half parts of dry sand, by weight, exposed to the air for twenty-four hours and then immersed in water for six days, must have a tensile strength of not less than 180 lbs. per square inch.

(109) That cement must be ground so fine that 90 per cent of it will pass through a sieve of 10,000 meshes per square inch.

(110) That pats of neat cement set in the air and then immersed in boiling water for twenty-four hours must show no checks or cracks.

(111) That cement must be sufficiently fresh to have lost no strength from age, but it must not be so fresh as to be " hot " and quick-setting. Neat cement at temperature of 70° F. must not take an initial set in less than thirty minutes, nor its final set in less than one hour.

(112) That the contractor must provide adequate storage and enough cement ahead to enable seven-day tests to be made before cement has to be used.

(113) That the contractor must furnish every reasonable facility to the inspectors for drawing samples of cement, and not less than ten days (holidays and Sundays excluded) must elapse between time of drawing the samples and using the cement.

(114) That cement must at all times be protected from dampness, air-currents, or other source of injury.

(115) That the laboratory tests given above are not final. Should the engineer at any time deem any lot of cement damaged or question-

able in any respect, the same shall be rejected, although it may previously have met other tests.

(116) That cement must be delivered on the work in barrels of 375 lbs. net weight, or in sacks of 94 lbs. net weight.

Engineer Corps, U. S. Army, 1902.

(1) The cement shall be an American Portland, dry and free from lumps. By a Portland cement is meant the product obtained from the heating or calcining up to incipient fusion of intimate mixtures, either natural or artificial, of argillaceous with calcareous substances, the calcined product to contain at least 1.7 times as much of lime, by weight, as of the materials which give the lime its hydraulic properties, and to be finely pulverized after said calcination, and thereafter additions or substitutions for the purpose only of regulating certain properties of technical importance to be allowable to not exceeding 2 per cent of the calcined product.

(2) The cement shall be put up in strong, sound barrels well lined with paper, so as to be reasonably protected against moisture, or in stout cloth or canvas sacks. Each package shall be plainly labeled with the name of the brand and of the manufacturer. Any package broken or containing damaged cement may be rejected or accepted as a fractional package, at the option of the United States agent in local charge.

(3) Bidders will state the brand of cement which they propose to furnish. The right is reserved to reject a tender for any brand which has not established itself as a high-grade Portland cement and has not for three years or more given satisfaction in use under climatic or other conditions of exposure of at least equal severity to those of the work proposed.

(4) Tenders will be received only from manufacturers or their authorized agents.

(The following paragraph will be substituted for paragraphs 3 and 4 above when cement is to be furnished and placed by the contractor:

No cement will be allowed to be used except established brands of high-grade Portland cement which have been made by the same mill and in successful use under similar climatic conditions to those of the proposed work for at least three years.)

(5) The average weight per barrel shall not be less than 375 lbs. net. Four sacks shall contain one barrel of cement. If the weight as deter-

mined by test weighings is found to be below 375 lbs. per barrel, the cement may be rejected, or, at the option of the engineer officer in charge, the contractor may be required to supply, free of cost to the United States, an additional amount of cement equal to the shortage.

(6) Tests may be made of the fineness, specific gravity, soundness, time of setting, and tensile strength of the cement.

(7) **Fineness.**—Ninety-two per cent of the cement must pass through a sieve made of No. 40 wire, Stubbs gauge, having 10,000 openings per square inch.

(8) **Specific gravity.**—The specific gravity of the cement, as determined from a sample which has been carefully dried, shall be between 3.10 and 3.25.

(9) **Soundness.**—To test the soundness of the cement, at least two pats of neat cement mixed for five minutes with 20 per cent of water by weight shall be made on glass, each pat about 3 inches in diameter and $\frac{1}{2}$ inch thick at the center, tapering thence to a thin edge. The pats are to be kept under a wet cloth until finally set, when one is to be placed in fresh water for twenty-eight days. The second pat will be placed in water which will be raised to the boiling-point for six hours, then allowed to cool. Neither should show distortion nor cracks. The boiling test may or may not reject at the option of the engineer officer in charge.

(10) **Time of setting.**—The cement shall not acquire its initial set in less than forty-five minutes and must have acquired its final set in ten hours.

(The following paragraph will be substituted for the above in case a quick-setting cement is desired:

The cement shall not acquire its initial set in less than twenty nor more than thirty minutes, and must have acquired its final set in not less than forty-five minutes nor in more than two and one-half hours.)

The pats made to test the soundness may be used in determining the time of setting. The cement is considered to have acquired its initial set when the pat will bear, without being appreciably indented, a wire $\frac{1}{64}$ inch in diameter loaded to weigh $\frac{1}{4}$ lb. The final set has been acquired when the pat will bear, without being appreciably indented, a wire $\frac{1}{24}$ inch in diameter loaded to weigh 1 lb.

(11) **Tensile strength.**—Briquettes made of neat cement, after being kept in air for twenty-four hours under a wet cloth and the balance of the time in water, shall develop tensile strength per square inch as follows:

After seven days, 450 lbs.; after twenty-eight days, 540 lbs.

Briquettes made of 1 part cement and 3 parts standard sand, by weight, shall develop tensile strength per square inch as follows:

After seven days, 140 lbs.; after twenty-eight days, 220 lbs.

(In case quick-setting cement is desired, the following tensile strength shall be substituted for the above:

Neat briquettes: After seven days, 400 lbs.; after twenty-eight days, 480 lbs.

Briquettes of 1 part cement to 3 parts standard sand: After seven days, 120 lbs.; after twenty-eight days, 180 lbs.)

(12) The highest result from each set of briquettes made at any one time is to be considered the governing test. Any cement not showing an increase of strength in the twenty-eight-day tests over the seven-day tests will be rejected.

(13) When making briquettes neat cement will be mixed with 20 per cent of water by weight, and sand and cement with 12½ per cent of water by weight. After being thoroughly mixed and worked for five minutes, the cement or mortar will be placed in the briquette mold in four equal layers, and each layer rammed and compressed by thirty blows of a soft brass or copper rammer three-quarters of an inch in diameter (or seven-tenths of an inch square, with rounded corners), weighing 1 lb. It is to be allowed to drop on the mixture from a height of about half an inch. When the ramming has been completed, the surplus cement shall be struck off and the final layer smoothed with a trowel held almost horizontal and drawn back with sufficient pressure to make its edge follow the surface of the mold.

(14) The above are to be considered the minimum requirements, Unless a cement has been recently used on work under this office, bidders will deliver a sample barrel for test before the opening of bids. If this sample shows higher tests than those given above, the average of tests made on subsequent shipments must come up to those found with the sample.

(15) A cement may be rejected in case it fails to meet any of the above requirements. An agent of the contractor may be present at the making of the tests, or, in case of the failure of any of them, they may be repeated in his presence. If the contractor so desires, the engineer officer in charge may, if he deem it to the interest of the United States, have any or all of the tests made or repeated at some recognized standard testing laboratory in the manner herein specified. All expenses of such tests to be paid by the contractor. All such tests shall be made on samples furnished by the engineer officer from cement actually delivered to him.

U. S. Reclamation Service, 1904.

1. **Definition.**—The cement shall be high-grade Portland cement. By the term Portland cement is to be understood the material obtained by finely pulverizing clinker produced by burning to semi-fusion an intimate mixture of finely ground calcareous and argillaceous materials.

2. **Composition.**—It must be of normal composition, in which the proportion of the sum of calcium oxide and alkalies to the sum of the silica, alumina, and ferric oxide must not be less than 1.7 to 1 nor more than 2.2 to 1. It shall not contain over 3 per cent of magnesia nor 2½ per cent of sulphate of lime. But in certain cases where such amounts of these substances are objectionable the engineer in charge may specify lower percentages. Its freedom from uncombined lime shall be determined as in article 12. The question of adulteration may be determined either by chemical analyses or by inspection of the process at the factory.

3. **Bids.**—Bids will be received only from manufacturers or their authorized agents, and the name of the brand offered shall in all cases be stated.

4. **Weight per barrel or sack.**—The average weight per barrel shall not be less than 375 lbs. net. Four sacks shall contain 1 barrel of cement. If the weight as determined by test weighings is found to be below 375 lbs. per barrel, the contractor may be required to supply free of cost to the United States, an additional amount of cement equal to the shortage.

5. **Barrels: damaged cement.**—If the cement is delivered in barrels, the barrels shall be strong and lined with paper, and the cement shall be free from lumps. Any package that is broken or that contains damaged cement may be rejected by the United States agent in local charge.

6. **Sampling.**—Samples of cement are to be taken from the barrels or sacks with a sampling-tube in such manner as to secure fair average of the packages. They are to be taken from every tenth barrel or fortieth sack, and numbered, and the packages from which they are taken to be sealed and corresponding numbers attached for future identification. The quantities taken are to be kept separate and tested separately. When the results of tests indicate variation in the quality of the cement, additional barrels or sacks will be sampled and tested.

7. **Aeration and testing.**—No cement shall be shipped until at least sixty days after its manufacture, except that in case of an emergency, and with the approval of the engineer in charge, a shorter time may be allowed, but if the cement shows indications of unsoundness, a longer

time may be required. The contractor shall keep in storage, in sacks or barrels, such stocks of cement as the engineer shall require, free of expense to the United States, for sampling and testing during a period of twenty-eight days.

8. **Shipment.**—The engineer shall give notice in writing to the contractor of the approximate requirements for cement shipments and of dates for sampling. In all cases the contractor shall be responsible for the delivery of the cement in good condition at the place of consignment.

9. **Factory inspection.**—The Government engineer, or his authorized agent, shall at all times have liberty to inspect the materials, process of manufacture, and daily laboratory records of analyses and tests at the cement works.

10. **Fineness.**—Ninety-five per cent by weight must pass through a No. 100 sieve having 10,000 meshes per square inch, the wire to be No. 40 Stubbs wire gauge; and 75 per cent by weight must pass through a No. 200 sieve having 40,000 meshes per square inch, the wire to be No. 48 Stubbs wire gauge.

11. **Specific gravity.**—The specific gravity of the cement shall not be less than 3.

12. **Soundness.**—Pats are to be made of neat mortar of normal consistency. The pats are to be molded on glass plates. They are to be circular in shape, 3 inches in diameter, $\frac{1}{2}$ inch thick in the center, and drawn to a thin edge at their circumference, and are to be kept under a wet cloth, or in a moist atmosphere, until finally set. One pat is to be put in water, the temperature of which is to be raised to the boiling-point and kept at that point for six hours. If the pat softens, cracks, warps, or disintegrates, the cement is unsound.

13. **Time of setting.**—The cement shall not acquire its initial set in less than forty-five minutes, and must acquire its final set within twelve hours. The pats made to test the soundness may be used in determining the time of setting. The cement is considered to have acquired its initial set when the pat will bear, without being appreciably indented, a wire $\frac{1}{12}$ inch in diameter loaded to weigh one-fourth lb. The final set has been acquired when the pat will bear, without being appreciably indented, a needle $\frac{1}{24}$-inch in diameter loaded to weigh 1 lb.

14. **Making briquettes.**—In making briquettes, neat cement mortar of normal consistency will be used. The mortar will be thoroughly mixed with a trowel and kneaded into the molds with the thumbs, a blunt stick, or a plunger. Six briquettes will be made from each sample. In making sand briquettes, the proportions shall be one part by weight of cement to three parts of standard crushed quartz sand and about

half as much water as is used for neat briquettes. Six briquettes will be made from each sample.

15. **Tensile strength.**—The neat briquettes prepared as specified above shall stand a minimum tensile strain per square inch as follows:

For one day in air and six days in water..... 450 lbs.
For one day in air and twenty-seven days in water.. 550 "

The sand-mortar briquettes, prepared as specified above, shall stand a minimum tensile strain per square inch as follows:

After one day in air and six days in water..... 175 lbs.
After one day in air and twenty-seven days in water 225 "

16. **Requirements.**—The above are to be considered the minimum requirements. The neat tests are to be considered of less value than those of sand and cement. The twenty-eight-day tests must always be higher than the seven-day tests. A cement may be rejected which fails to meet any of the above requirements.

Canadian Society of Civil Engineers.*

The whole of the cement is to be well-burned pure Portland cement, of the best quality, free from free lime, slag dust, or other foreign material.

(1) **Fineness.**—The cement shall be ground so fine that the residue on a sieve of 10,000 meshes to the square inch shall not exceed 10 per cent of the whole by weight, and the whole of the cement shall pass a sieve of 2500 meshes to the square inch.

(2) **Specific gravity.**—The specific gravity of the cement shall be at least 3.09, and shall not exceed 3.25 for fresh cement, the term "fresh" being understood to apply to such cements as are not more than two months old.

(3) **Tests.**—The cement shall be subjected to the following tests:

(*a*) *Blowing test.*—Mortar pats of neat cement thoroughly worked shall be troweled upon carefully cleaned 5-inch by 2½-inch ground-glass plates. The pats shall be about ½ inch thick in the center and worked off to the sharp edges at the four sides. They shall be covered with a damp cloth and allowed to remain in the air until set, after which they shall be placed in vapor in a tank in which the water is heated

* Proposed Canadian standard specifications for Portland cement. Cement, vol. 4, pp. 98–99. May, 1903.

to a temperature of 130° F. After remaining in the vapor six hours, including the time of setting in air, they shall be immersed in the hot water and allowed to remain there for eighteen hours. After removal from the water the samples shall not be curled up, shall not have fine hair cracks, nor large expansion cracks, nor shall they be distorted. If separated from the glass, the samples shall break with a sharp, crisp ring.

(*b*) *Tensile test* (*neat cement*).—Briquettes made of neat cement mixed with about 20 per cent of water, by weight, after remaining one day in air, in a moist atmosphere, shall be immersed in water, and shall be capable of sustaining a tensile stress of 250 lbs. per square inch after submersion for two days, 400 lbs. per square inch after submersion for six days, 500 lbs. per square inch after submersion for twenty-seven days. The tensile test shall be considered as the average of the strength of five briquettes, and any cement showing a decrease in tensile strength on or before the twenty-eighth day shall be rejected.

(*Sand and cement*).—The sand for standard tests shall be clean quartz, crushed so that the whole shall pass through a sieve of 400 meshes to the square inch, but shall be retained on a sieve of 900 meshes per square inch. The sand and cement shall be thoroughly mixed dry, and then about 10 per cent of their weight of water shall be added, when the briquettes are to be formed in suitable molds. After remaining in a damp chamber for twenty-four hours the briquettes shall be immersed in water, and briquettes made in the proportion of one of cement to three of sand, by weight, shall bear a tensile stress of 125 lbs. per square inch after submersion for six days, and 200 lbs. per square inch after submersion for twenty-eight days. Sand and cement briquettes shall not show a decrease in tensile strength at the end of twenty-eight days or subsequently.

(4) The manufacturer shall, if required, supply chemical analyses of the cement.

(5) **Packing.**—The cement shall be packed either in stout air- and water-tight casks, carefully lined with strong brown paper, or in strong air- and water-tight bags.

(6) The manufacturer shall give a certificate with each shipment of cement, stating (1) the date of manufacture; (2) the tests and analyses which have been obtained for the cement in question at the manufacturer's laboratory; (3) that the cement does not contain any adulteration.

Concrete-steel Engineering Company.*

No cement will be allowed to be used except established brands of high-grade Portland cement which has been in successful use under similar conditions to the work proposed for at least three years, and has been seasoned or subjected to aeration for at least thirty days before leaving the factory. All cement shall be dry and free from lumps, and immediately upon receipt shall be stored in a dry, well-covered, and ventilated place thoroughly protected from the weather. If required the contractor shall furnish a certified statement of the chemical composition of the cement and of the raw material from which it is manufactured.

The fineness of the cement shall be such that at least 90 per cent will pass through a sieve of No. 40 wire, Stubbs gauge, having 10,000 openings per square inch, and at least 75 per cent will pass through a sieve of No. 45 wire, Stubbs gauge, having 40,000 openings per square inch.

Samples for testing may be taken from every bag or barrel, but usually for tests of 100 barrels a sample will be taken from every tenth barrel. The samples will be mixed thoroughly together while dry, and the mixture be taken as the sample for test.

Tensile tests will be made on specimens prepared and maintained until tested at a temperature not less than 60° F. Each specimen will have an area of 1 square inch at the breaking section and after being allowed to harden in moist air for twenty-four hours will be immersed and maintained under water until tested.

The sand used in preparing test specimens shall be clean, sharp, crushed quartz retained on a sieve of 30 meshes per lineal inch, and passing through a sieve of 20 meshes per lineal inch. In test specimens of one cement and three sand, no more than 12 per cent of water by weight shall be used. Specimens prepared from a mixture of one part cement and three parts sand, parts by weight, shall after seven days develop a tensile strength of not less than 170 lbs. per square inch, and not less than 240 lbs. per square inch after twenty-eight days. Cement mixed neat from 20 per cent to 25 per cent of water to form a stiff paste shall, after 30 minutes, be appreciably indented by the end of a wire inch $\frac{1}{12}$ in diameter loaded to weigh $\frac{1}{4}$ lb. Cement made into thin pats on glass plates shall not crack, scale, or warp under the fol-

* The specifications from which this section is taken were published in Cement, vol. 4, pp. 105–108, May, 1903. They are for concrete-steel structures on the Melan, Thacher and Von Emperger patents.

lowing treatment: Three pats will be made and allowed to harden in moist air at from 60° to 70° F.; one of these will be placed in fresh water for twenty-eight days, another will be placed in water which will be raised to the boiling-point for six hours and then allowed to cool, and the third is to be kept in the air of the prevailing outdoor temperature.

British Standard Specifications.*

Quality and preparation.—(1) The cement is to be prepared by intimately mixing together calcareous and argillaceous materials, burning them at a clinkering temperature and grinding the resulting clinker. No addition of any material is to be made after burning, except when desired by the manufacturer, and if not prohibited in writing by the consumer, in which case calcium sulphate or water may be used. The cement, if watered, shall contain not more than 2 per cent of water, whether that water has been added or has been naturally absorbed from the air. If calcium sulphate is used, not more than 2 per cent calculated as anhydrous calcium sulphate of the weight of the cement shall be added.

Sampling and preparation for testing and analysis.—(2) As soon as the cement has been bulked at the maker's works,† or on the works in connection with which the material is to be used, at the consumer's option, samples for testing are to be taken from each parcel, each sample consisting of cement from at least twelve different positions in the same heap, so distributed as to insure, as far as is practicable, a fair average sample of the whole parcel, all to be mixed together and the sample for testing to be taken therefrom.

(3) Before gauging the tests, the sample so obtained is to be spread out for a depth of 3 inches for twenty-four hours, in a temperature of 58° to 64° F.

(4) In all cases where consignments are of 100 tons and upwards samples selected as above from each consignment, either at the maker's works or after delivery at the works where the cement is to be used, are to be sent for expert testing and for chemical analysis. In no case is cement so tested and analyzed to be accepted or used unless previously certified in writing by the consumer to be of satisfactory quality. Payment for such tests and analyses to be made by the con-

* British standard specifications for Portland cement. Engineering News, vol. 53, pp. 227–228. March 2, 1905.

† Should the consumer desire to stipulate for any special quantity, the size of the heap should be stated.

sumer, the manufacturer supplying the cement required for the same free of charge. When consignments of less than 100 tons have to be supplied, the maker shall, if required, give certificates for each delivery, to the effect that such cement complies with the terms of this standard specification, with regard to quality, tests, and chemical analyses, no payment being made by the consumer for such certificate nor for the making of such tests and analyses.

(5) Should it be deemed more convenient by the consumers that the samples for testing should be taken at the makers' works before delivery, the latter are, in that event, to afford full facilities to the inspector who may be appointed by the consumers to sample the cement as he may desire at the makers' works, and subsequently to identify each parcel as it may be dispatched, with that sampled by him. No parcel is to be sent away unless a written order has been previously received by the makers from the said consumer to the effect that the material in question has been approved.

Fineness and sieves.—(6) The cement shall be ground to comply with the following degrees of fineness, viz.:

The residue on a sieve $76 \times 76 = 5776$ meshes per square inch is not to exceed 5 per cent.

The residue on a sieve $180 \times 180 = 32,400$ meshes per square inch is not to exceed $22\frac{1}{2}$ per cent.

The sieves are to be prepared from standard wire; the size of the wire for the 5776 mesh is to be .0044 inch and for the 32,400 mesh .0018 inch. The wire shall be woven (not twilled), the cloth being carefully mounted on the frames without distortion.

Specific gravity.—(7) The specific gravity of the cement shall be not less than 3.15 when sampled and hermetically sealed at the makers' works, nor less than 3.10 if sampled after delivery to the consumer.

Chemical composition.—(8) The cement is to comply with the following conditions as to its chemical composition. There shall be no excess of lime, that is to say, the proportion of lime shall be not greater than is necessary to saturate the silica and alumina present. The percentage of insoluble residue shall not exceed 1.5 per cent; that of magnesia shall not exceed 3 per cent, and that of sulphuric anhydride shall not exceed 2.5 per cent.

Tensile tests.—(9) The quantity of water used in gauging shall be appropriate to the quality of the cement, and shall be so proportioned that when the cement is gauged it shall form a smooth, easily worked paste that will leave the trowel cleanly in a compact mass. Fresh water is to be used for gauging, the temperature thereof, and of the test-

room at the time the said operations are performed, being from 58° to 64° F.

The cement gauged as above is to be filled, without mechanical ramming, into molds; each mold resting upon an iron plate until the cement has set. When the cement has set sufficiently to enable the mold to be removed without injury to the briquette, such removal is to be effected. The said briquettes shall be kept in a damp atmosphere and placed in fresh water twenty-four hours after gauging and kept there until broken, the water in which the test briquettes are submerged being renewed every seven days and the temperature thereof maintained between 58° and 64° F.

Neat tests.—(10) Briquettes of neat cement are to be gauged for breaking at seven and twenty-eight days, respectively, six briquettes for each period. The average tensile strength of the six briquettes shall be taken as the accepted tensile strength for each period. For breaking, the briquette is to be held in strong metal jaws, the briquettes being slightly greased where gripped by the jaws. The load must then be steadily and uniformly applied, starting from zero increasing at the rate of 100 lbs. in twelve seconds. The briquettes are to bear on the average not less than the following tensile stresses before breaking:

7 days from gauging.....400 lbs. per square inch of section.
28 days from gauging.....500 lbs. per square inch of section.

The increase from seven to twenty-eight days shall not be less than:

25% when the 7-day test falls between 400 to 450 lbs. per square inch.
20% when the 7-day test falls between 450 to 500 lbs. per square inch.
15% when the 7-day test falls between 500 to 550 lbs. per square inch.
10% when the 7-day test falls between 550 lbs. per square inch or upwards.

Sand tests.—(11) The cement should also be tested by means of briquettes prepared from one part of cement to three parts by weight of dry standard sand, the said briquettes being of the shape described for the neat-cement tests; the mode of gauging, filling the molds, and breaking the briquettes is also to be similar. The proportion of water used shall be such that the mixture is thoroughly wetted, and there shall be no superfluous water when the briquettes are formed. The cement and sand briquettes are to bear the following tensile stresses:

7 days from gauging.....120 lbs. per square inch of section.
28 days from gauging.....225 lbs. per square inch of section.

The increase from seven to twenty-eight days shall not be less than 20 per cent.

The standard sand referred to above is to be obtained from Leighton Buzzard. It must be thoroughly washed, dried, and pass through a sieve of 20×20 meshes per square inch, and must be retained on a sieve of 30×30 meshes per square inch, the wires of the sieve being .0164-inch and .0108-inch respectively.

Setting-time.—(12) There shall be three distinct gradations of setting-time, which shall be designated as "quick," "medium," and "slow."*

Quick.—The setting-time shall not be less than ten minutes or more than thirty minutes.

Medium.—The setting-time shall not be less than half an hour or more than two hours.

Slow.—The setting-time shall not be less than two hours or more than five hours.*

The temperature of the air in the test-room at the time of gauging and of the water used is to be between 58° and 64° F.

The cement shall be considered as "set" when a needle having a flat end $\frac{1}{16}$ inch square, weighing in all $2\frac{1}{2}$ lbs., fails to make an impression when its point is applied gently to the surface.

Soundness.—(13) The cement shall be tested by the Le Chatelier method, and is in no case to show a greater expansion than 12 millimeters after twenty-four hours' aeration and 6 millimeters after 7 days' aeration.

Note.—The apparatus for conducting the Le Chatelier test consists of a small split cylinder of spring brass or other suitable metal of 0.5 millimeter (.0197 inch) in thickness, 30 millimeters (1.1875 inches) internal diameter, and 30 millimeters high, forming the mold, to which on either side of the split are attached two indicators 165 millimeters (6.5 inches) long from the center of the cylinder, with pointed ends.

In conducting the test the mold is to be placed upon a small piece of glass and filled with cement gauged in the usual way, care being taken to keep the edges of the molds gently together while this operation is being performed. The mold is then covered with another glass plate, a small weight is placed on this, and the mold is immediately placed in water at 58° to 64° F. and left there for twenty-four hours.

The distance separating the indicator points is then measured and the mold placed in cold water, which is brought to the boiling-point in

* When a specially slow-setting cement is required the minimum time of setting shall be specified.

15 to 30 minutes and kept boiling for six hours. After cooling, the distance between the points is again measured; the difference between the two measurements represents the expansion of the cement, which must not exceed the limits laid down in this specification.

(14) The tests and analyses hereinbefore referred to shall in no case relate to a larger quantity of cement than 250 tons sampled at one time.

Acceptance.—(15) No cement is to be approved or accepted unless it fully complies with the foregoing conditions.

American Society for Testing Materials, 1909.

GENERAL OBSERVATIONS.

1. These remarks have been prepared with a view of pointing out the pertinent features of the various requirements and the precautions to be observed in the interpretation of the results of the tests.

2. The committee would suggest that the acceptance or rejection under these specifications be based on tests made by an experienced person having the proper means for making the tests.

3. **Specific gravity.**—Specific gravity is useful in detecting adulteration or underburning. The result of tests of specific gravity are not necessarily conclusive as an indication of the quality of the cement, but when in combination with the results of other tests may afford valuable indications.

4. **Fineness.**—The sieves should be kept thoroughly dry.

5. **Time of setting.**—Great care should be exercised to maintain the test pieces under as uniform conditions as possible. A sudden change or wide range of temperature in the room in which the tests are made, a very dry or humid atmosphere, and other irregularities vitally affect the rate of setting.

6. **Tensile strength.**—Each consumer must fix the minimum requirements for tensile strength, to suit his own conditions. They shall, however, be above the minimum later stated.

7. **Constancy of volume.**—The tests for constancy of volume are divided into two classes, the first normal, the second accelerated. The latter should be regarded as a precautionary test only, and not infallible. So many conditions enter into the making and interpreting of it that it should be used with extreme care.

8. In making the pats the greatest care should be exercised to avoid initial strains due to molding or to too rapid drying out during the first twenty-four hours. The pats should be preserved under the most

uniform conditions possible, and rapid changes of temperature should be avoided.

9. The failure to meet the requirements of the accelerated tests need not be sufficient cause for rejection. The cement may, however, be held for twenty-eight days and a retest made at the end of that period. Failure to meet the requirements at this time should be considered sufficient cause for rejection, although in the present state of our knowledge it cannot be said that such failure necessarily indicates unsoundness, nor can the cement be considered entirely satisfactory simply because it passes the tests.

STANDARD SPECIFICATIONS FOR CEMENT.

1. **General conditions.**—All cement shall be inspected.

2. Cement may be inspected either at the place of manufacture or on the work.

3. In order to allow ample time for inspecting and testing, the cement should be stored in a suitable weather-tight building having the floor properly blocked or raised from the ground.

4. The cement shall be stored in such a manner as to permit easy access for proper inspection and identification of each shipment.

5. Every facility shall be provided by the contractor and a period of at least twelve days allowed for the inspection and necessary tests.

6. Cement shall be delivered in suitable packages with the brand and name of manufacturer plainly marked thereon.

7. A bag of cement shall contain 94 lbs. of cement net. Each barrel of Portland cement shall contain 4 bags, and each barrel of natural cement shall contain 3 bags, of the above net weight.

8. Cement failing to meet the seven-day requirements may be held awaiting the results of the twenty-eight-day tests before rejection.

9. All tests shall be made in accordance with the methods proposed by the Committee on Uniform Tests of Cement of the American Society of Civil Engineers, presented to the society Jan. 21, 1903, and amended Jan. 20, 1904, and Jan. 15, 1908, with all subsequent amendments thereto.

10. The acceptance or rejection shall be based on the following requirements:

PORTLAND CEMENT.

18. **Definition.**—This term is applied to the finely pulverized product resulting from the calcination to incipient fusion of an intimate mixture of properly proportioned argillaceous and calcareous materials, and to

which no addition greater than 3 per cent has been made subsequent to calcination.

19. **Specific gravity.**—The specific gravity of the cement, thoroughly dried at 100° C., shall be not less than 3.10.

20. **Fineness.**—It shall leave by weight a residue of not more than 8 per cent on the No. 100, and not more than 25 per cent on the No. 200-sieve.

21. **Time of setting.**—It shall develop initial set in not less than thirty minutes, but must develop hard set in not less than one hour, nor more than ten hours.

22. **Tensile strength.**—The minimum requirements for tensile strength for briquettes one inch square in section shall be as follows, and shall show no retrogression in strength within the periods specified:

NEAT CEMENT.

Age.	Strength.
24 hours in moist air	175 lbs.
7 days (1 day in air, 6 days in water)	500 "
28 days (1 day in air, 27 days in water)	600 "
One Part Cement, Three Parts Sand:	
7 days (1 day in moist air, 6 days in water)	200 "
28 days (1 day in moist air, 27 days in water)	275 "

23. **Constancy of volume.**—Pats of neat cement about three inches in diameter, one-half inch thick at the center, and tapering to a thin edge, shall be kept in moist air for a period of twenty-four hours.

(*a*) A pat is then kept in air at normal temperature and observed at intervals for at least 28 days.

(*b*) Another pat is kept in water maintained as near 70° F. as practicable, and observed at intervals for at least 28 days.

(*c*) A third pat is exposed in any convenient way in an atmosphere of steam, above boiling water, in a loosely closed vessel for five hours.

24. These pats, to satisfactorily pass the requirements, shall remain firm and hard and show no signs of distortion, checking, cracking or disintegration.

25. **Sulphuric acid and magnesia.**—The cement shall not contain more than 1.75 per cent of anhydrous sulphuric acid (SO_3), nor more than 4 per cent of magnesia (MgO).

United States Government Specification, 1917. Revised to Date.

1. Portland cement is the product obtained by finely pulverizing clinker produced by calcining to incipient fusion, an intimate and properly proportioned mixture of argillaceous and calcareous materials, with no additions subsequent to calcination excepting water and calcined or uncalcined gypsum.

2. The following limits shall not be exceeded:

	Per Cent.
Loss on ignition	4.00
Insoluble residue	0.85
Sulphuric anhydride (SO_3)	2.00
Magnesia (MgO)	5.00

3. The specific gravity of cement shall not be less than 3.10 (3 07 for white Portland cement). Should the test of cement as received fall below this requirement a second test may be made upon an ignited sample. The specific gravity test will not be made unless specifically ordered.

4. The residue on a standard No. 200 sieve shall not exceed 20 per cent by weight.*

5. A pat of neat cement shall remain firm and hard, and show no signs of distortion, cracking, checking or disintegration in the steam test for soundness.

6. The cement shall not develop initial set in less than forty-five minutes when the Vicat needle is used or sixty minutes when the Gillmore needle is used. Final set shall be attained within ten hours.

7. The average tensile strength in pounds per square inch of not less than three standard mortar briquettes composed of one part cement and three parts standard sand, by weight, shall be equal to or higher than the following:

Age at Test.	Storage of Briquette.	Tensile Strength, Lbs. per Sq. In.
7 days	1 day in moist air; 6 days in water	200
28 days	1 day in moist air; 27 days in water	300

8. The average tensile strength of standard mortar at twenty-eight days shall be higher than the strength at seven days.

9. The cement shall be delivered in suitable bags or barrels with the brand and name of the manufacturer plainly marked thereon, unless shipped in bulk. A bag shall contain 94 pounds net. A barrel shall contain 376 pounds net.

* Increased from 22 per cent on July 1, 1918.

10. The cement shall be stored in such a manner as to permit easy access for proper inspection and identification of each shipment, and in a suitable weather-tight building which will protect the cement from dampness.

11. Every facility shall be provided the purchaser for careful sampling and inspection at either the mill or at the site of the work, as may be specified by the purchaser. At least ten days from the time of sampling shall be allowed for the completion of the seven-day test, and at least thirty-one days shall be allowed for the completion of the twenty-eight day test. The cement shall be tested in accordance with methods hereinafter prescribed. The twenty-eight-day test shall be waived only when specifically so ordered.

12. The cement may be rejected if it fails to meet any of the requirements of these specifications.

13. Cement shall not be rejected on account of failure to meet the fineness requirement if upon retest after drying at 100° C. for one hour it meets this requirement.

14. Cement failing to meet the test for soundness in steam may be accepted if it passes a retest using a new sample at any time within twenty-eight days thereafter.

15. Packages varying more than 5 per cent from the specific weight may be rejected; and if the average weight of packages in any shipment, as shown by weighing 50 packages taken at random, is less than that specified, the entire shipment may be rejected.

16. Tests may be made on individual or composite samples as may be ordered. Each test sample should weigh at least 8 lbs.

17. (*a*) *Individual Sample.*—If sampled in cars one test sample shall be taken from each 50 barrels or fraction thereof. If sampled in bins one sample shall be taken from each 100 barrels.

(*b*) *Composite Sample.*—If sampled in cars one sample shall be taken from 1 sack in each 40 sacks (or 1 barrel in each 10 barrels) and combined to form one test sample. If sampled in bins or warehouses, one test sample shall represent not more than 200 barrels.

18. Cement may be sampled at the mill by any of the following methods that may be practicable, as ordered:

(*a*) *From the conveyor delivering to the bin.*—At least 8 lbs. of cement shall be taken from approximately each 100 barrels passing over the conveyor.

(*b*) *From filled bins by means of proper* sampling tubes.—Tubes inserted vertically may be used for sampling cement to a maximum depth of 10 feet. Tubes inserted horizontally may be used where the

construction of the bin permits. Samples shall be taken from points well distributed over the face of the bin.

(c) *From filled bins at points of discharge.*—Sufficient cement shall be drawn from the discharge openings to obtain samples representative of the cement contained in the bin, as determined by the appearance at the discharge openings of indicators placed on the surface of the cement directly above these openings before drawing of the cement is started.

19. Samples preferably shall be shipped and stored in air-tight containers. Samples shall be passed through a sieve having 20 meshes per linear inch in order to thoroughly mix the sample, break up lumps, and remove foreign materials.

The remaining items of these government specifications deal with details of testing methods, chemical and physical. These are omitted here, as such matters are discussed in other chapters of this volume.

PART VII. PUZZOLAN CEMENTS.

CHAPTER XXXIX.

PUZZOLANIC MATERIALS IN GENERAL.

PUZZOLANIC materials include all those natural or artificial materials which are capable of forming hydraulic cements on being simply mixed with lime, without the use of heat. Many materials possess this property, but relatively few have ever attained to sufficient commercial importance to be discussed here. In composition the puzzolanic materials are largely made up of silica and alumina, usually with more or less iron oxide; some, as the slags used in cement-manufacture, carry also notable percentages of lime. As might be inferred from this composition, most of the puzzolanic materials possess hydraulicity to a greater or less degree of themselves, but the addition of lime usually greatly increases their hydraulic power.

The term *puzzolan*, here adopted for this group of cementing materials, is a corruption of the adjective form of the name *pozzuolana*. It has no particular etymological excuse for existence, but will be accepted in this volume for the sake of uniformity, as it seems to have been adopted by various authorities in the United States.

Natural Puzzolanic Materials.

Natural puzzolanic materials are quite widely distributed, though they have never attained much commercial importance, save in Europe. As regards their origin, they are of two classes: In the first class may be included all those which are the direct products of volcanic action, the material being a fine volcanic ash or dust deposited either on the slopes of the volcano or carried by the wind to lakes or streams in which the ash is deposited. This group includes the more active puzzolanic materials, its chief representatives being pozzuolana proper, santorin, tosca, tetin and trass. It may be noted that in origin materials

of this class resemble closely the granulated slags used in slag-cement manufacture both volcanic ashes and granulated slags being due to the processes of (1) fusion of a silico-aluminous material, and (2) rapid cooling of the resulting product by ejection into air or immersion in water. The second class includes a number of less important (because less active) hydraulic materials, such as arênes, psammites, etc., which are materials resulting from the decay of certain igneous rocks.

The principal natural puzzolanic materials will be discussed separately, in the following order: Pozzuolana (tosca, tetin), trass, santorin, arênes.

Pozzuolana.—Pozzuolana derives its name from the little town of Pozzuoli, located a few miles west of Naples, at which point the material was first obtained by the Greek colonists, and at a later date by the Romans. The material has also been exploited at other points near Rome and Naples.

TABLE 235.

ANALYSES OF POZZUOLANA FROM ITALY.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	H_2O
1	58.58	22.74		4.06	1.37			
2	52.66	14.33	10.33	7.66	3.86	4.13		7.03
3	44.5	15.0	12.0	8.8	4.7	1.4	4.0	9.2
4	63.18	19.8		5.68	0.35			
5	60.91	21.28	4.76	1.90	0.00	4.37	6.23	
6	44.0	10.5	29.5	10.0	tr.	1.00		2.5
7	44.5	15.75	16.3	8.96	tr.	11.0		3.5
8	46.0	16.5	15.5	10.0	3.0	4.0		5.0
9	44.5	15.5	12.5	9.5	4.4	10.27		3.33
10	39.0	14.0	13.0	18.0	3.0	11.0		
11	56.31	15.23	7.11	1.74	1.36	6.54	2.84	6.12

1. Pozzuolana, Rome. Stanger and Blount, Mineral Industry, vol. 5, p. 71.
2. " St. Paul's Caves Thoyn, Dict. App. Chem., 3d ed., vol. 1, p. 475.
3. " Civita Vecchia. Berther, Anal. Gillmon, Limes, Cements, and Mortars, p. 125.
4. " Naples. Stanger and Blount, Mineral Industry, vol. 5, p. 71.
5. " " Stengel, Anal. Zervas, School of Mines, Quart., vol. 18, p. 230.
6. " Vesuvius. Brown. Thorpe, Dict. App. Chem., 3d ed., vol. 1, p. 475.
7. " " " " " " 3d ed., vol. 1, p. 475.
8. " " Dark gray. Thorpe, Dict. App. Chem., 3d ed., vol. 1, p. 475.
9. " " Light gray. Thorpe, Dict. App. Chem., 3d ed., vol. 1, p. 475.
10. Lava, Vesuvius, 1868. Thorpe, Dict. App. Chem., 3d ed., vol. 1, p. 475.
11. Tuff, Monte Nuova. Merrill, Rocks, Rock Weathering and Soils, p. 141.

Most of the Italian pozzuolana is obtained from small open cuts, or pits, though some of these workings are now of great depth. Those of Trentaremi, for example, are about 600 feet deep. The various deposits differ greatly in the quality of the materials obtained from them. Care should therefore be exercised in selecting a spot for exploita-

tion, and sorting of the material dug would be advisable in order to keep the product of uniformly high grade. After extraction the material is screened and ground. In addition it is occasionally slightly roasted, which process increases its hydraulic properties. Carelessness, both in the mining and in the later preparation of the pozzuolana, has brought the Italian article somewhat into disrepute among European engineers. In consequence it is losing ground with respect both to pozzuolana from the Azores and to trass from Rhenish Prussia.

Pozzuolana is also obtained at a number of localities in southeastern France. These localities occur mostly in three areas: (1) in the Auvergne Mountains, lying in the Departments of Puy de Dôme and Cantal; (2) in the Mountains du Vivarais, between Haute Loire and Ardêche; and (3) in the Department of l'Hérault, near the Gulf of Lyons.

TABLE 236.

ANALYSES OF POZZUOLANA FROM FRANCE.

	1.	2.	3.	4.	5.	6.	7.
Silica (SiO_2)	47.9	47.1	46.05	48.0	35.09	30.73	38.50
Alumina (Al_2O_3)	34.2	39.0	17.0	36.4	17.65	11.63	18.35
Iron oxide (Fe_2O_3)			20.55		16.82	24.92	14.90
Lime (CaO)	8.2	7.0	8.55	8.10	4.26	3.73	8.70
Magnesia (MgO)	3.9	tr.	tr.	tr.	3.17	2.49	tr.
Alkalies (K_2O,Na_2O)	2.6	4.7	6.35	4.8	n. d.	n. d.	7.30
Water (H_2O)	3.2	2.2	1.6	2.4	19.06	19.02	7.75

1. Auvergne Mountains black. Thorpe, Dict. App. Chem., vol. 1, p. 475.
2. " " reddish-brown. Thorpe, Dict. App. Chem., vol. 1, p. 475.
3. " " brick-red. Thorpe, Dict. App. Chem., vol. 1, p. 475.
4. " " Gravenvére. Thorpe, Dict. App. Chem., vol. 1, p. 475.
5. Vivarais Mountains, gray. Vicat, analyst.
6. " " brown. Vicat, analyst.
7. Department of l'Hérault, brown. Vicat analyst.

Pozzuolana has been shipped from San Miguel and Terceira in the Azores, to Portugal for over a hundred years, and has been used with very satisfactory results in many important buildings, harbor works, etc. The Azores pozzuolana varies in color from yellowish to brownish, and sometimes to grayish. It is frequently so fine-grained as not to require screening or grinding before use. A reddish colored variety from the same islands is termed tetin.

A similar ash, locally called "tosca," is obtained from Teneriffe, one of the Canary Islands, and shipped to Spain for use as a cementing material.

TABLE 237.

ANALYSES OF POZZUOLANA FROM THE AZORES ISLANDS.

	1.	2.	3.
Silica (SiO_2)	60.90	54.70	57.73
Alumina (Al_2O_3)	11.14	20.50	13.81
Iron oxide (Fe_2O_3)	12.78	6.30	12.02
Lime (CaO)	2.57	2.20	3.74
Magnesia (MgO)	1.45	1.70	1.73
Potash (K_2O)	2.64	2.20	3.21
Soda (Na_2O)	2.74		2.76
Water (H_2O)	5.78	12.40	4.66

1. From St. Miguel.—Tetin. Zervas, analyst. School of Mines Quarterly, vol. 18, p. 230.
2. " " —Pozzuolana. Chateau, analyst. School of Mines Quarterly, vol. 18, p. 230.
3. " Terceira. Zervas, analyst. School of Mines Quarterly, vol. 18, p. 230.

Volcanic materials of a type somewhat different from normal pozzuolana occur on l'Ile Bourbon, a French island lying about 400 miles east of Madagascar.

ANALYSIS OF VOLCANIC ASH, ILE BOURBON.

Silica (SiO_2)	25.67
Alumina (Al_2O_3)	16.33
Iron oxide (Fe_2O_3)	40.00
Magnesia (MgO)	tr.
Water (H_2O)	17.00

Trass.—Trass is a pale yellowish to grayish rock, rough to the feel, composed of an earthy or compact pumiceous dust mixed with fragments of pumice, trachyte, carbonized wood, etc. It is, so far as origin is concerned, an ancient volcanic mud. Trass occurs along the Rhine in Rhenish Prussia, from Köln on the north to Coblenz on the south. The towns of Brohl, Kruft, Plaidt, and Andernach, all located northwest of Coblenz and within fifteen miles of that city, are prominent points in connection with the trass industry. A series of analyses of trass and related products is given in Table 238.

Santorin.—The island of Santorin, or Thera, is one of the most southeasterly of the islets of the Grecian Archipelago, lying in the Cyclades group. An ash called in commerce " santorin," derived from the volcano of the same name, is quite extensively shipped for use as a cementing material.

TABLE 238.

ANALYSES OF TRASS AND RELATED MATERIALS FROM GERMANY.

	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	H_2O
1	46.25	20.71	5.48	2.15	1.00	6.30		9.25
2	46.6	20.6	12.0	3.0	....	5.0		12.8
3	48.94	18.95	12.34	5.41	2.42	0.37	3.56	11.94
4	53.07	18.28	3.43	1.24	1.31	4.17	3.73	12.78
5	53.58	19.11	9.24	3.21	0.30	4.84	1.87	7.50
6	54.0	16.5	6.1	4.0	0.7	10.0		7.0
7	55.28	17.34	3.90	3.17.	0.87	4.70	3.80	10.63
8	57.0	16.0	5.0	2.6	1.0	7.0	1.0	9.6
9	57.5	10.1	3.9	7.7	1.1	6.4		12.6
10	58.32	20.88	4.15	2.19	1.10	3.91	4.11	5.87
11	61.10	12.70	10.20	8.10	1.90	2.10	2.10	1.40
12	59.40	22.70	2.50	3.10	0.80	3.50	2.80	4.80
13	60.49	19.95	9.37	3.12	1.43	3.40		1.33
14	62.83	21.55	4.11	0.72	0.42	3.35	3.02	4.19
15	66.39	17.74	4.97	0.53	0.47	3.05	1.94	4.89
16	67.60	11.30	5.20	8.20	2.80	0.60	0.50	3.10

1. Trass. Rhenish. Thorpe, Dict. App. Chem., 3d ed., vol. 1, p. 475.
2. " Dutch. Thorpe, p. 475.
3. " Andernach. Thorpe, p. 475.
4. " Plaidt. von Decken, Anal. Zirkel, Lehrbuch der Petrographie, 1894, vol. 3, p. 678.
5. " " Zervas, Anal. Zervas, School of Mines Quart., vol. 18, p. 230.
6. " Andernach. Chatoney and Rivol, Anal. Zirkel, p. 678.
7. " Kruft. Mengerschausen, Anal. Zervas, p. 320.
8. " Brohl. Berthier, Anal, Gillmore, Limes, Cements, and Mortars, p. 125.
9. " Andernach. Chatoney and Rivol, Anal. Zirkel, p. 678.
10. " Brohl. Bruhus, Anal. Zirkel, p. 678.
11. " " Kyll, Anal. Zervas, p. 320.
12. Trachyte tuff. Siebengebirge, Kyll, Anal. Zervas, p. 320.
13. " " Laacher See. Merrill, Rocks, Rock Weathering and Soils, p. 141.
14. " " Siebengebirge. Bischof, Anal. Zirkel, p. 675.
15. " " " von der Marck, Anal. Zirkel, p. 675.
16. Leucite tuff. Weibern. Kyll, Anal. Zervas, p. 320.

TABLE 239.

ANALYSES OF SANTORIN ASH, FROM SANTORIN.

	1.	2.	3.	4.
Silica (SiO_2)	72.84	71.44	63.07	66.37
Alumina (Al_2O_3)	12.26	9.87	15.67	13.72
Iron oxide (Fe_2O_3)	4.35	3.84	8.73	4.31
Lime (CaO)	2.55	2.64	3.83	2.98
Magnesia (MgO)	1.58	1.84	1.93	1.29
Potash (K_2O)	1.28	1.86	1.87	2.83
Soda (Na_2O)	2.65	3.74	3.86	4.22
Water (H_2O)	2.25	4.61	1.14	4.06

1. Pumiceous portion. Feichtinger, analyst. Thorpe, Dict. App. Chem., vol. 1, p. 476.
2. Fine ash. " " " " " " vol. 1, p. 476.
3. Obsidian particles. " " " " " " vol. 1, p. 476.
4. Average sample. " " School of Mines Quarterly, vol. 18, p. 230.

Arênes, etc.—The materials called "arênes", by early French writers on cement technology are sands and residual material derived from

the decay of various igneous rocks, and particularly from the decay of the more basic rocks, such as trap, basalt, etc. Such materials will naturally vary greatly in composition and properties, but all of them agree in possessing feeble hydraulicity. For present-day commercial purposes they are practically worthless.

TABLE 240.

ANALYSES OF ARÊNES, FRANCE.

	1.	2.	3.	4.	5.
Silica (SiO_2)	38 54	60.33	42.10	38.50	60.30
Alumina (Al_2O_3)	20.00	21.43	23.65	29.40	23.70
Iron oxide (Fe_2O_3)	12.00	8.57	22.47	18.10	10.30
Lime (CaO)	8.00[1]	6.69	tr.	2.00	tr.
Magnesia (MgO)	n. d.		.....	.....	2.50
Alkalies (K_2O,Na_2O)	n. d.	n. d.	1.28	1.50	3.20

[1] Lime carbonate ($CaCO_3$).

1. Saint Astier, Department Dordogne. Vicat, analyst.
2. Brest. Vicat, analyst.
3. Saint Servan. Vicat, analyst.
4. " " " "
5. Chateaulin. " "

As might be inferred from the examples given, natural materials showing slightly hydraulic properties are not of rare occurrence. With the exception of trass, santorin and pozzuolana proper, these materials are rarely sufficiently hydraulic to be of service as bases for puzzolan cements or mortars. The feebly hydraulic materials have, however, a practical value which may be noted briefly here. It is—that, owing to the fact that they are hydraulic, they can be profitably substituted in places where they occur for common sand in mortar.

Chelius has tested * the fine material remaining after the crushing of basalt in an ordinary stone-crusher. This fine material (dust and screening) gave the following results as compared with normal sand:

TABLE 241.

STRENGTH OF BASALTIC DUST.

	Tension.			Compression.		
	28 Days.	90 Days.	1 Year.	28 Days.	90 Days.	1 Year.
Cement and normal sand	....	20.9	....	....	237.7	
Cement and basalt fines	....	43.6	....	....	320.8	
Lime and normal sand	6.3	....	8.5	14.2	....	35.8
Lime and basalt fines	7.7	....	11.1	44.9	....	67.8

* Journ. Soc. Chem. Ind., vol. 19, p. 826.

Part of the superiority, as shown by these tests, of the basalt dust to normal sand is probably due to purely physical causes. In part, however, it is probably due to the fact that the finely crushed basalt acted as a puzzolanic material.

Range of average composition of natural puzzolanic materials.—From the separate tables of analyses given in preceding paragraphs the following table of average analyses have been prepared:

TABLE 242.

AVERAGE ANALYSES OF NATURAL PUZZOLANIC MATERIALS.

	Pozzuolana, Italy.	Pozzuolana, France.	Pozzuolana, Asores.	Trass, Germany.	Santorin.	Average Natural Pozzolanic Material.
Number of analyses	9	7	3	11	1	31
Silica (SiO_2)	50.98	41.91	57.78	53.78	66.37	51.08
Alumina (Al_2O_3)	15.55	16.16	15.15	17.38	13.72	16.30
Iron oxide (Fe_2O_3)	14.41	19.30	10.37	6.89	4.31	11.13
Lime (CaO)	7.39	6.93	2.84	3.89	2.98	5.46
Magnesia (MgO)	1.96	1.37	1.63	1.17	1.29	1.50
Alkalies (K_2O,Na_2O)	6.63	5.15	4.52	6.82	7.05	6.21
Water (H_2O)	5.09	7.89	7.61	9.22	4.06	7.64

Puzzolanic materials in the United States.—Volcanic ash and other materials which may be expected to show puzzolanic action occur extensively in the western United States, but few tests appear to have been made of their hydraulic properties.

Mr. J. S. Diller, in a recent description * of the mineral resources of the Redding district of California, has noted that a " tuff, bordering the northern end of the Sacramento Valley, is very like the trass of the Rhine Valley. This is especially true of that on Stillwater, near the Copper City road, or east of Millville, and at a number of points on the western side of the Sacramento Valley. The limestone and the tuff are at several places within a few miles of each other, and there is reason to believe that a good quantity of hydraulic cement may be made from them within convenient reach of the railroad. This matter is of importance in the construction of large dams for irrigation or water-power in the Redding region. Similar volcanic products occur in Arizona, and have been used locally as puzzolanic materials.

* Bulletin 225, U. S. Geological Survey, p. 177, 1904.

Artificial Materials.

Blast-furnace slag is by far the most prominent of the artificial materials. Other artificial materials have, however, been used for this purpose, burnt clay being one of the better known of these minor products.

Burnt clay.—The following recent note * is of interest in the present connection.

"Mortar composed of lime and burnt clay was used extensively in constructing the Asyût Barrage completed in 1902, across the Nile, and described in detail in a paper by Mr. George Henry Stephens, M. Inst. C. E., to the institution of Civil Engineers on March 15, 1904. After being burnt the clay was ground and passed through a 100-mesh sieve. The best results were had with a clay burnt to a light terra-cotta color as compared with clay burned brick-red and clay burned dark red to purple. The ground clay was mixed with slaked lime and sand was added to form a mortar. The following are the results of long-time tensile tests made with various mixtures moulded into standard briquettes kept in water after twelve hours in air":

TABLE 243.

STRENGTH OF LIME—BURNT-CLAY MORTARS.

Mixture by Volume.	Age 1 Year.	Pounds per Square Inch.	Age 2 Years.	Pounds per Square Inch.
3 clay 2 lime	Maximum..... Average of 52 samples.	400 272	Maximum..... Average of 56 samples...	410 320
1 clay 1 lime	Maximum..... Average of 38 samples.	305 239	Maximum..... Average of 25 samples...	350 291
¾ clay 1 lime ¾ sand	Maximum..... Average of 37 samples.	320 259	Maximum..... Average of 55 samples...	376 280

Blast-furnace slags.—Slags, according to the general use of that term, are the fusible silicates formed during metallurgical operations by the combination of the fluxing materials with the gangue of the ore. The composition of the slag, therefore, depends upon the character and relative proportions of the gangue and the fluxes. The slag will, in general, contain only those elements present in either gangue or flux; though it may contain also a percentage, usually small, of the

* Engineering News, vol. 53, p. 177. Feb. 16, 1905.

metal which is being reduced, and its composition may, in some processes, be slightly modified by the presence of the elements taken up from the fuel. The slags or "cinders" obtained in refining the metals differ from the normal slags in that they may contain a very appreciable percentage of metal, sufficient in many cases to justify further treatment of the slag in order to recover its metallic contents. As this utilization of such slags is entirely a metallurgical operation, they will not be further discussed in the present volume.

While many elements may occur in slags, those which are of universal or even common occurrence are relatively few. The slags most commonly formed are silicates, consisting essentially of silica, oxides of the alkaline elements, and certain metallic oxides, these last, with the exception of alumina, being usually present in small quantity only. In certain metallurgical operations, however, the percentage of metallic oxides may rise so as to make them important ingredients in the slag. According to the processes, ores or fluxes used, slags may also contain more or less phosphoric anhydride, sulphur and fluorine.

The particular use, or uses to which the slag from any given furnace may be most profitably put, will depend upon several factors. When considering possible utilizations, the most important factor will generally be found to be the chemical composition of the slag. It is true that, for certain uses, as for example highway macadam and railroad ballast, the physical condition of the slag is of rather more importance than its chemical composition; but the two utilizations named are among the less profitable, and are only to be considered when the slag cannot be disposed of more profitably. Local conditions, under which head may be grouped questions of furnace management, possible markets, and transportation routes and charges, will be found to be of great economic importance. These factors are, however, too variable to be discussed in the present volume, with one exception. The exception noted is the effect of slag utilization upon the general furnace management. The furnace manager who is endeavoring to profitably utilize his slag will often find it necessary to consider how far he may economically go in changing details of his main process in order to increase the value of his by-product. This is particularly the case where the slag is used for cement.

Blast-furnace slags of certain types have been used extensively in Europe, and to a less extent in the United States, in the manufacture of slag cement. The following chapters will therefore be devoted to a discussion of the materials, manufacture and properties of slag cements.

CHAPTER XL.

SLAG CEMENT. REQUISITES AND TREATMENT OF THE SLAG.

SLAG cement is at present by far the most important member of the group of puzzolan cements, so that its manufacture will be described in some detail.

Summary of general methods of manufacture.—Slag cement is composed of an intimate mechanical mixture of slaked lime and granulated blast-furnace slag of suitable chemical composition; both materials being finely pulverized before, during or after mixing. The process of manufacture includes the granulating and drying of the slag, the slaking of the lime, the mixing of these materials, and the grinding of the resulting cement, together with any means which may be employed for the regulation of the setting time of the cement.

These different factors in the manufacture will be described in the order named above. In the present chapter, the character and treatment of the slag will be taken up.

Composition of the Slag.

Requisite chemical composition of slag.—The slag used in cement-manufacture must be a basic blast-furnace slag. Tetmajer, the first investigator of slag cements, announced as the results of his experiments (*a*) that the hydraulic properties of the slag increased with the proportion of lime contained in it, and that slags in which the ratio $\frac{CaO}{SiO_2}$ was so low as to approach unity were valueless for cement-manufacture; (*b*) that, so far as the alumina content of the slag was concerned, the best results were obtained when the ratio $\frac{Al_2O_3}{SiO_2}$ gave a value of 0.45 to 0.50; and (*c*) that with any large increase of alumina above the amount indicated by this value of the alumina-silica ratio, the tendency of the cement to crack (when used in air) was increased.

Prost, at a later date, investigated the subject, using for experiment several commercial slags and also a series prepared from pure CaO, SiO_2, and Al_2O_3. He decided that the hydraulic properties (both

as regards rapidity of set and ultimate strength) of the slag increased as the proportions of lime and alumina increased; and failed to find any indication that a high alumina content causes disintegration. His best results were obtained from slags having the compositions respectively of $2SiO_2$, Al_2O_3, $3CaO_3$, and $2SiO_2$, Al_2O_3, $4CaO$.

Mahon, in 1893, made a series of experiments to determine the value (for cement-manufacture) of a large series of the slags produced by the furnaces of the Maryland Steel Company: and found that the slags giving the best results were two having respectively the following compositions:

(1) SiO_2, 30%; Al_2O_3, 17%; CaO, 47.5%; S, 2.38%; and SiO_2, 25.3%; Al_2O_3, 20.1%; CaO, 48%; S, 3.63%.

The ratios of $\frac{CaO}{SiO_2}$ and $\frac{Al_2O_3}{SiO_2}$, calculated for these slags are:

(1) $\frac{CaO}{SiO_2}=1.58$; $\frac{Al_2O_3}{SiO_2}=0.57$; and (2) $\frac{CaO}{SiO_2}=1.9$; $\frac{Al_2O_3}{SiO_2}=0.79$.

At the close of the experiments Mahon recommended that slags be used slightly higher in alumina than those above quoted.

Composition of slags actually used.—The specifications under which slag from the furnaces was accepted by the cement department of the Illinois Steel Company were:

(1) Slag must analyze within the following limits:

$SiO_2+Al_2O_3$ not over 49%; Al_2O_3, from 13 to 16%; MgO, under 4%.

(2) Slag must be made in a hot furnace and must be of a light-gray color.

(3) Slag must be thoroughly disintegrated by the action of a large stream of cold water directed against it with considerable force. This contact should be made as near the furnace as is possible.

A series of over 300 analyses of slags used by this company in their slag (puzzolan) cement, show the following range in composition:

SiO_2, 29.60 to 35.60%; Al_2O_3, and Fe_2O_3, 12.80 to 16.80%; CaO, 47.99 to 50.48%; MgO, 2.09 to 2.81%.

The requirements of the Birmingham Cement Company as to the chemical composition of the slags used for cement are: that the lime content shall not be less than 47.9 per cent; that the silica and lime together shall approximately amount to 81 per cent; and that the alumina and iron oxide together shall equal from 12 to 15 per cent.

Analyses of a number of slags used in slag-cement manufacture are shown in Table 244. The analyses of foreign slags are quoted from various reliable authorities and the analyses of the Illinois Steel Com-

pany slags have beens elected from a large series published in the report of the U. S. Army Board of Engineers to show the extreme ranges of the different elements. The ratios $\frac{CaO}{SiO_2}$ and $\frac{Al_2O_3}{SiO_2}$ have been calculated for each slag and are shown in this table.

TABLE 244.

ANALYSES OF SLAGS USED FOR SLAG CEMENT.

Components.	Middlesboro, England.		Harzb'g, Germany (used at Brunswick).	Belgium.	Bilbao, Spain.		Chiondez, Switzerland.		
SiO_2...	30.00	31.50	30.72	32.51	32.90	38.00	26.88	27.33	26.24
Al_2O_3..	28.00	18.56	16.40	13.19	13.25	10.00	24.12	23.81	24.74
FeO...	0.75	.....	0.43	0.48	0.46	.....	0.44	0.63	0.49
CaO..	32.75	42.22	48.59	44.75	47.30	46.00	45.11	45.83	46.83
MgO..	5.25	3.18	1.28	2.20	1.37	.....	1.09	0.92	0.88
CaS...	1.90	.....	2.16	4.90	3.42	.....	1.80	1.34	0.59
$CaSO_4$	.....	.....	.....	.....	.....	.....	.....	0.17	0.32
SO_2...	.....	0.45							
S.....	.....	2.21							
MnO_2.	0.60	0.44	tr.	0.60	1.13	.....	0.50		
$\frac{CaO}{SiO_2}$..	1.09	1.34	1.58	1.37	1.44	1.21	1.68	1.67	1.78
$\frac{Al_2O_3}{SiO_2}$..	0.93	0.59	0.53	0.43	0.41	0.27	0.89	0.87	0.93

Components.	Saulnes, France.		Marnaval (used at Donjeux).		Pont-a-Mousson.	Chicago, Ill.			
SiO_2...	31.65	31.50	28.35	28.00	32.00	32.20	33.10	31.80	34.30
Al_2O_3..	17.00	16.62	18.15	19.5	22.0	15.50	12.60	14.80	14.76
FeO...	0.65	0.62	1.50	....	4.00+ MgO				
CaO..	47.20	46.10	47.40	45.0	42.00	48.14	49.98	49.74	48.11
MgO..	1.36	.....	2.45	.....	See FeO	2.27	2.45	2.29	2.66
S.....	.....	.....	1.40						
MnO_2.	0.85								
$\frac{CaO}{SiO_2}$..	1.49	2.46	1.67	1.61	1.31	1.49	1.51	1.56	1.40
$\frac{Al_2O_3}{SiO_2}$..	0.53	0.52	0.64	0.69	0.68	0.48	0.38	0.46	0.43

From these data it can be seen that the ratio of alumina to silica is carried very high at Choindez, and is rather low at Chicago, relatively to most of the European plants. It must be remembered, however, that one reason for carrying a high alumina-silica ratio does not apply at Chicago, as there rapidity of set is gained by the use of the Whiting process. Taking these two plants as representative of the

best European and American practice, the average of the analyses given shows the ratios actually used to be: Choindez, Switzerland, $\frac{CaO}{SiO_2}=1.71$, $\frac{Al_2O_3}{SiO_2}=0.90$; and Chicago, Ill., $\frac{CaO}{SiO_2}=1.49$, $\frac{Al_2O_3}{SiO_2}=0.44$.

These results may be compared with the theoretical ratios advised by Tetmajer, Prost, and Mahon, and discussed on a previous page of the present Chapter.

Selection of slags.—The erection of a slag-cement plant in connection with any given furnace is not justified, unless a sufficient amount of the slags usually produced will fall within slag-cement requirements, as these requirements have been outlined above in the section on chemical composition of the slag. In a large plant it will usually be easy to secure a constant supply of slag of proper composition without interfering with the proper running of the furnaces. In a small plant, however, or in one running on a number of different ores, such a supply may be difficult to obtain. These points, of course, should be settled in advance of the erection of the cement-plant.

In the case of any given furnace running on ores and fluxes, which are fairly steady in composition and proportions, the selection of the slag used for cement-making may be largely based on its color, checked if necessary by rapid determinations of lime. The darker-colored slags are generally richest in lime, except when the depth of color is due to the presence of iron; the lighter-colored slags are usually higher in silica and alumina. Candlot states further * in this connection that the slag issuing at the commencement and toward the end of a discharge should be rejected because of the air-chilling which attends its slow movement.

Granulating the Slag: Methods and Effects.

Assuming that a slag of proper composition has been selected, the first step in the actual manufacture of slag cement will be the "granulation" of the molten slag. Granulation is the effect produced by bringing molten slag into contact with a sufficient amount of cold water. The physical effect of this proceeding is to cause the slag to break up into porous particles ("slag sand"). Granulation has also certain chemical effects, highly important from an economic point of view, which will be discussed later.

Methods of granulating the slag.—The success of the granulation depends on bringing the slag into contact with the water as soon as

* Ciments et chaux hydrauliques.

possible after it has left the furnace. The effects of the process will be found to vary with, (*a*) the temperature of the slag at the point of contact; (*b*) the temperature of the water; (*c*) the amount of water used, and (*d*) its method of application.

Taking up the last point first it may be noted that two general methods of application of the water have been used. In the first method the stream of slag, as it issued from the furnace, was struck by a jet of steam under pressure. This method, which was used at one time in slag-cement plants in the Middlesboro district, England, had the effect of blowing the slag into fine threads with attached globules. It is, in fact, much the same as the process still used in the manufacture of mineral wool. From an economic point of view it had the distinct advantage of putting the slag in a condition in which it was easily pulverized by the grinding-machinery; but it had certain inconveniences, and has been almost or entirely superseded by the method now to be mentioned.

The second way in which the water may be applied is to allow the stream of slag as it issues from the furnace to fall into a trough containing a rapidly flowing stream of cold water. Care must be taken that the fall into the trough is not too great, and that the stream of water is deep enough and fast enough, for otherwise the slag will acquire sufficient momentum in its fall to solidify in a mass on the bottom of the trough. This method is in use at all slag-cement plants of the present day, being occasionally modified by the use (either in addition to or in place of the flowing stream of water in the trough) of a jet of water playing on the slag before it strikes the trough.

The following two examples, taken from present-day practice at American slag-cement plants, will serve to indicate two methods, differing in minor details only of slag granulation.

At the first plant the furnaces are located on an embankment about 8 feet above and 20 feet away from a standard gauge-switch track. A rectangular trench about 1 foot in width is dug from the furnace to near the edge of the embankment. Here a section of semicircular sheet-iron troughing, 12 to 15 inches in diameter and about 10 feet in length, meets the trench. The inner end of the trough is fixed, and is at such a level that the bottom of the trough is about 6 inches below the bottom of the trench. The outer end of the trough is free and supported by wire ropes so that it can be readily swung into position over a box car on the switch track below.

As already noted, the bottom of the earthen trench is about 6 inches above the bottom of the iron trough. This is done to allow the inser-

tion at this end of the trough of a 3-inch water-pipe. Slag from the furnace flows through the trench and into the trough, which is set at an inclination of about 1 inch in 10. Water is injected through the 3-inch pipe, under 10 or 15 feet head, into the trough. If enough water is used, the slag will be granulated as soon as it enters the trough, and will be readily carried down it into the car below, rarely flowing with a greater depth than 6 inches in the trough. If insufficient water is used the slag puffs up and fills the trough, so that the slag-mass has to be broken into with an iron rod and pushed along.

The car into which the slag flows is provided with four 3-inch holes in its sides, to allow the surplus water to escape.

At another slag-cement plant recently visited by the writer, the granulated slag is caught in cylindrical masonry tanks, 15 feet in diameter and 10 feet in depth. The stream of molten slag flows from the furnace to and over the edge of the tank and through a semi-circular trough about 10 inches in diameter, which enters the tank at its top rim and projects 6 inches over the edge. About 6 inches below the bottom of this trough a pipe, carrying cold water under slight pressure, enters the tank, projecting into it for 4 inches. This pipe is 3 inches in diameter for most of its length, but the portion projecting into the tank is flattened so as to give an orifice 4 or 5 inches wide and about half an inch high. The stream of slag, flowing slowly along the trough and over the edge of the tank, is struck by the jet of cold water from the pipe, and is granulated. The granulated slag is taken from the tank by bucket elevators running continuously.

Effects of granulating the slag.—The physical effect of causing hot slag to come in contact with cold water is to break the slag up into small porous particles. As this materially aids in pulverizing the slag, it is probable that granulation would be practiced on this account alone. But as a matter of fact, granulation has in addition to its purely physical result two important chemical effects. One is to make the slag, if it be of suitable chemical composition, energetically hydraulic; the other is to remove a portion of the sulphides contained in the slag in the form of hydrogen disulphide.

Le Chatelier states that the hydraulic properties of granulated slag are due to the presence of a silico-alumino ferrite of calcium corresponding in composition to the formula $3CaO$, Al_2O_3, $2SiO_2$. This compound appears also in Portland cements, but in them it is entirely inert, owing to the slow cooling it has undergone. When, however, as in the case of granulated slags, it is cooled with great suddenness, it becomes an important hydraulic agent. When so cooled " it is attackable by

weak acids and also by alkalies. It combines particularly with hydrated lime in setting, and gives rise to silicates and aluminates of lime identical with those which are formed by entirely different reactions during

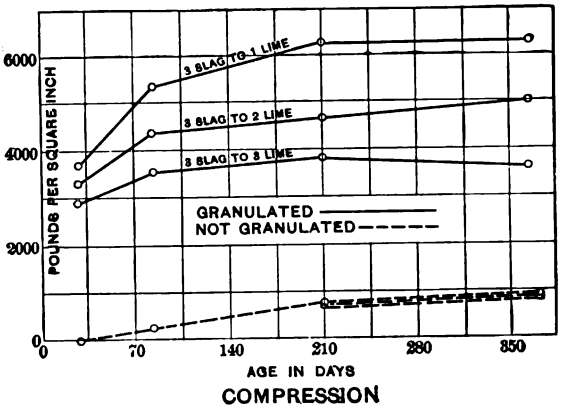

FIG. 152.

the setting of Portland cement. It is upon this property that the manufacture of slag cements, which assumes daily greater importance, is based."

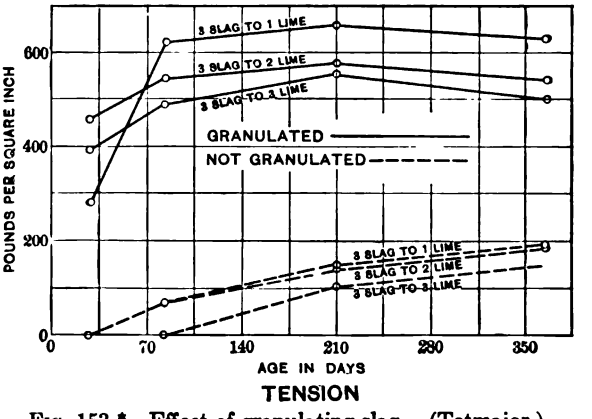

FIG. 153.*—Effect of granulating slag. (Tetmajer.)

Increased hydraulicity due to granulation.—The striking increase in the hydraulic properties of the slag when it is granulated was well brought out by Prost's investigations. The following table (245), giving the results of tests of tensile and compressive strength of briquettes of

* From Johnson's "Materials of Construction," p. 190.

both granulated and ungranulated slag, as determined by Prost, is of interest in this connection. The results of other tests, by Tetmajer, are shown diagrammatically in Figs. 152 and 153.

TABLE 245.

STRENGTH OF GRANULATED AND UNGRANULATED SLAG. (PROST.)

Proportion of Mixture by Weight.	Resistance in Kilograms per Square Centimeter.							
	28 Days.		84 Days.		210 Days.		360 Days.	
	Tension.	Compression.	Tension.	Compression.	Tension.	Compression.	Tension.	Compression.
33 parts lime, 100 parts slag:								
Granulated	33.7	259.9	43.5	377.5	46.4	440.5	44.4	438.7
Not granulated	0	0	5.4	0	10.7	50.5	13.8	59.9
66 parts lime, 100 parts slag:								
Granulated	32.1	233.7	38.1	308.2	40.5	326.7	35.3	350.9
Not granulated	0	0	5.4	0	10.5	54.1	13.3	62.4
100 parts lime, 100 parts slag:								
Granulated	27.6	205.2	34.3	248.9	38.9	267.8	38.1	253.1
Not granulated	0	0	0	0	7.6	47.6	10.8	63.8

Desulphurization due to granulation.—When molten slag is poured into water, a very large proportion of the sulphur contained in the slag is carried off by the water. The extent to which the desulphurizing of the slag is secured by the simple method of granulating is shown by the following result from actual practice at the slag brick works at Kralovedvoor, Bohemia. Here the slag is granulated, just as in slag-cement works, by running it into flowing cold water. Examination * of the water used showed that it had increased in temperature from 14½° C. to about 56° C., and that it carried in 10,000 parts the following parts of mineral matter in solution:

SiO_2	0.426
$CaSO_4$	0.749
$FeSO_4$	0.108
$MgSO_4$	0.448
Na_2SO_4	0.178
NaCl	0.038
Na_2SiO_2	0.693
CaS	0.271
H_2S	0.047
	2.958

* Engineering and Mining Journal, April 16, 1898.

Drying the Slag.

The slag as it is brought to the cement mill from the granulating tanks carries from 15 to over 40 per cent of water absorbed during granulation. As will be noted later attempts have been made to utilize this contained water in the slaking of the lime, but these attempts have hitherto proved unsuccessful. As the manufacture is at present conducted, therefore, the large percentage of water carried by the slag is of no service, and in order to get good results from the grinding machinery the water must be removed as completely as possible before pulverization is attempted.

Before describing the various types of driers in use, a few words on the general problem may be serviceable. The slag may carry, as above noted, from 15 to over 40 per cent of water, varying with the method of granulation, the fineness of grain, etc. In test runs slag can be thoroughly granulated without the use of more than 10 to 15 per cent of water, but in actual practice it will usually be found that the granulated slag carries from 30 to 45 per cent. As the slag must be reduced to extreme fineness it is necessary that this moisture be reduced as much as possible. With a well-conducted rotary drier it is possible to economically reduce the percentage of moisture in the dried product to about one-fourth of one per cent.

The temperature to which the product is carried in drying is not a matter of serious moment so long as it does not pass the point at which the slag begins to re-fuse. Theoretically, of course, it is necessary only to carry the temperature above 212° F., but in practice it is economically impossible to keep it as low as this. It may be carried as high as a dull-red heat without injury to the slag. Indeed, it is probably the case that drying at relatively high temperatures improves the hydraulic properties of the slag, rather than otherwise, as it is well known that the natural puzzolanic materials are improved by roasting. It would not, therefore, be a matter of surprise if drying the slag at a higher temperature than is actually necessary should result in materially accelerating the set of the resulting cement and also in increasing the strength of briquettes made from it.

The Ruggles-Coles drier (see Fig. 161) consists of two concentric hollow cylinders bolted together and revolving on an axis slightly inclined from the horizontal. The outside cylinder is made of steel plates, the longitudinal seams having butt joints with inside lapping straps. The inner cylinder, which is also made of steel, is connected with the outer cylinder at its middle by heavy cast-iron arms *A* solidly riveted to

both cylinders, while the cylinders are further connected at each end by two sets of adjustable or swinging arms *B*, which prevent the joints being affected by the expansion or contraction of the cylinders. At the head or upper end the inner cylinder projects beyond the outer cylinder, passing into a stationary head or air chamber *E* to the hot air flue *D* of the furnace *G* with which it is connected. At the lower or discharge end is another stationary head *E* forming an air chamber, through an opening in the bottom of which the dried material is discharged. This head is supplied with a damper to regulate the temperature, which gives perfect control.

The cylinders are set at an inclination of about $\frac{3}{8}$ inch to the foot. The outer cylinder is secured to two heavy rolled steel-bearing rings, which rest and revolve upon eight bearing wheels supported by oscillating arms or rockers. The lateral motion of the cylinder is taken

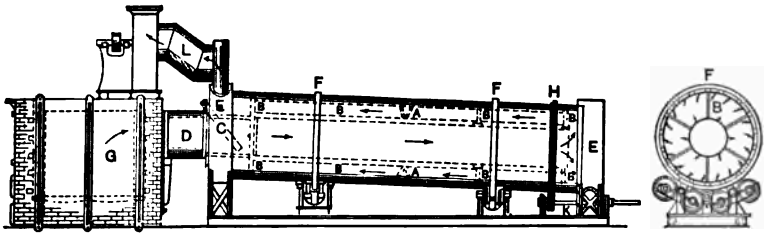

FIG. 154.—Ruggles-Coles drier.

up by four thrust wheels. The drier is revolved by a cast gear *H* secured to the outer cylinder, and this is driven by a shaft and pinion *K* extended beyond the end of the machine and supported in two babbitted journal boxes fitted to the frame. The entire machine is fitted and secured to a heavy frame of 8-inch I beams braced and framed together and usually set on a concrete foundation. The exhaust fan is placed where most convenient to drive, and is connected with the outer cylinder by a suitable flue *L*. The furnace *G* is built independent of the rest of the drier, and is connected with the head end of the inner cylinder by an iron flue *D* built with fire-brick. A specially designed burner is substituted for the furnace when oil, gas, or powdered coal are to be used.

The heated air passes through the inner cylinder (which is shown by the dotted lines in the illustration) and returns, between the inner and outer cylinders, to the fan. The direction of the hot-air current is shown by arrows. The wet raw material is fed into the space between the inner and outer cylinders through a spout *C* in the stationary

head at the upper end of the drier. The material is picked up by buckets or carriers fastened to the inner surface of the outer cylinder, and is carried partly around during the rotation of the drier. On dropping from these buckets it is caught by flights fastened to the outer surface of the inner cylinder. These flights carry the material partly around and then drop it on the outer cylinder, when the cycle of operations commences again. While the movements of the material are occurring, it is being dried both by the heated-air current which flows through the space between the two cylinders, and by contact with the warm outer surface of the inner cylinder; and it is also being carried slowly toward the lower or discharge end of the machine.

The following table shows working results obtained in the use of the Ruggles-Coles drier on blast-furnace slag at various slag-cement plants:

TABLE 246.

WORKING RESULTS OF RUGGLES-COLES DRIER.

User.	Number of Driers.	Original Percentage Moisture.	Final Percentage Moisture.	Water Evaporated per Hour.
Knickerbocker Cement Co.	1	41.82	0.29	4401 lbs.
Maryland Cement Co.....	2	20.32	0.25	4114 "
Birmingham Cement Co...	2	45	....	4181 "
Southern Cement Co.....	2	40	....	4707 "
Stewart Cement Co.....	3	12.85	....	2271 "

User.	Dry Material Delivered per Hour.	Coal Used per Hour.	Water Evaporated per Pound of Coal.
Knickerbocker Cement Co.....	6,399 lbs.	560 lbs.	7.87 lbs.
Maryland Cement Co.....	16,173 "	542 "	7.59 "
Birmingham Cement Co.....	4,987 "	537 "	7.60 "
Southern Cement Co.....	7,061 "	550 "	8.56 "
Stewart Cement Co.....	15,408 "	334 "	6.80 "

The Holst drier is used at Donjeux and Mallstadt, and consists essentially of a sheet-iron cylinder 9 meters long and 0.8 meter in diameter, into which the slag is fed automatically by a screw feed. In the cylinder a helical screw revolves on a hollow central shaft, causing the slag to advance slowly through the cylinder. The fireplace is below and near one end of the cylinder and the heat is caused to pass under the cylinder to the other end, thence through the hollow shaft to the stack in a direction contrary to that in which the slag is moving. The cylinder is protected from the direct flame by brickwork. This appa-

ratus dries from 7 to 8 metric tons of slag per day with a coal consumption of about 5 per cent of the weight of slag dried.

At Vitry, France, a simple and effective non-rotary drier, operated by gravity, is employed, plan and section of which is given in Fig. 155. It consists of drying compartments (each of which is lettered, *a*, *b*, *c*, *d*, in the plan), arranged about a central flue (*c*, *d*, *c*, *d* in plan), through which passes the heated gases from a furnace. The central flue is 1 meter square; the drying compartments 0.5×1 meter in area, and both are 7 meters in height. Each of the drying compartments contains 10

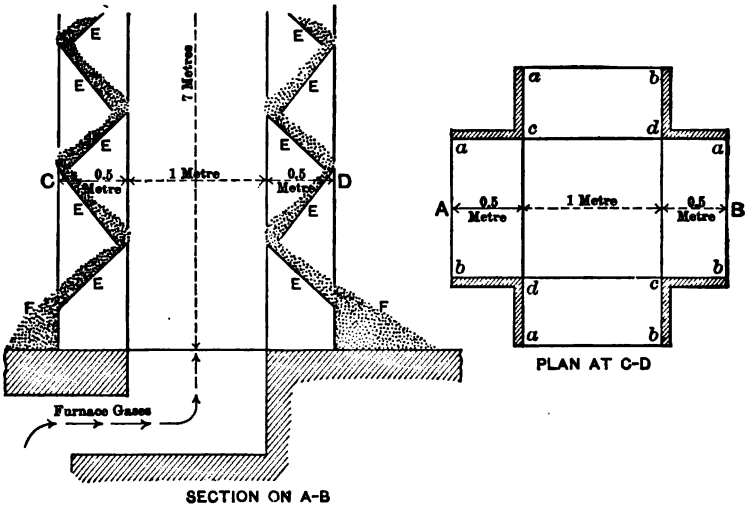

Fig. 155.—Vitry slag-drier.

sheet-iron plates (of which only 6, *E*, are shown in each, compartment of the section). These plates are inclined and so arranged that the wet slag, shoveled in at the top of each compartment, descends by gravity and finally issues from the lowest plate in the heaps *F*, from which it is shoveled and sent to the grinding mills. According to Prost, a drier of this type and size will dry from 12 to 15 metric tons of slag per working day. From 6 to 6.5 lbs. of coke are necessary to dry each 100 lbs. of slag.

Tower driers, resembling those used at one or two American Portland cement plants, could of course be used in drying slag. At present, however, every slag-cement plant in the United States uses rotary driers.

CHAPTER XLI.

SLAG CEMENT: LIME, MIXING AND GRINDING.

AFTER the slag has been granulated and dried, as described in the preceding chapter, it must be mixed with a carefully slaked lime, in proper proportions, and the mixture must be finely ground. These points will be taken up first in the present chapter after which data on the general processes and costs of slag-cement manufacture will be presented.

Composition and selection of the lime.—The lime used for admixture with the slag may be either a quicklime (common lime) or a hydraulic lime. In usual American practice, and also at most European plants, a common or quicklime is used. At a few American, French, and German plants, however, limes which have more or less hydraulic properties are employed. Prost has carried on experiments touching this point and decided that the use of a hydraulic lime did not noticeably increase the tensile strength of the resulting cement, but that it did increase the value of the product in another way. This incidental advantage is that slag cements made by using hydraulic lime are less liable to fissure and disintegrate when used in air or in dry situations than cement in which common quicklime is used. As above noted, this method of improving the product has been tried, to the writer's knowledge, at only a few of the American plants. At Königshof, Germany, the general practice at which plant is described on page 605, a somewhat hydraulic lime is used, whose analysis will serve as fairly representative of materials of this type, though most hydraulic limes would run considerably higher in silica and alumina.

ANALYSIS OF HYDRAULIC LIME, KÖNIGSHOF, GERMANY.

	Per Cent.
Silica (SiO_2)	12.421
Alumina (Al_2O_3)	2.620
Iron oxide (Fe_2O_3)	0.883
Manganese oxide (MnO_2)	tr.
Lime (CaO)	81.546
Magnesia (MgO)	1.751
Soda (Na_2O)	0.211
Carbon dioxide (CO_2)	0.194
Moisture (H_2O)	0.425

The following analyses are of limes used at different slag-cement plants in the United States:

TABLE 247.

ANALYSES OF LIMES USED IN AMERICAN SLAG-CEMENT PLANTS.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	3.24	3.50	1.62	10.20	0.78	1.38
Alumina (Al_2O_3)	4.26	3.92	2.62	3.60	0.52	0.62
Iron oxide (Fe_2O_3)						
Lime (CaO)	81.92	83.20	82.40	81.33	98.40	97.80
Magnesia (MgO)	n. d.	n. d.	n. d.	1.17	0.10	0.18

Of the analyses above tabulated, it will be seen that Nos. 1 to 4 inclusive are of the semi-hydraulic type whose value has been noted. Analyses 5 and 6, on the other hand, are representative of the very pure limes used at most slag-cement plants.

Burning the lime.—As a matter of convenience, and also to reduce freight charges, the limestone is burned near the quarry. The subject of burning the lime requires only brief mention here, as it involves no points of particular interest or novelty. Only two minor details demand notice, as affecting the value of the cement. The first is, that the lime should be burned as thoroughly as possible, for unburned lumps of limestone are absolutely valueless to the cement-manufacturer, and must be removed before mixing with the slag. The second point to be noticed is, that the lime should be shipped to the cement-plant as soon as possible after it is burned, in order to prevent any considerable proportion of it from air-slaking. Air-slaked particles, while not absolutely inert, are still of little value to the cement.

Slaking the lime.—The granulated slag as it comes to the mill from the tanks to which it is carried in granulating it carries a very large percentage of water. The amount of water carried will vary in practice at different plants between 25 and 50 per cent as limits. Early in the history of slag-cement manufacture attempts were made to utilize this surplus water. To this end the wet slag was mixed with dry unslaked lime, the expectation being that the water in the slag would serve to slake the lime. In practice, however, it was soon found that this plan was not successful. The lime was only partially—and very irregularly—slaked, and the mixture was not left in such a condition as to be economically handled by the pulverizing machinery. In present-day practice, therefore, the lime is slaked previous to being mixed with the slag.

Sieving and grinding the lime.—If lime has been thoroughly burned and carefully slaked it will all be in the form of a very fine powder, much finer than can be obtained by any economically practicable grinding-machinery. In practice, however, it will be found that after slaking the lime has not all fallen to powder, but still contains a certain proportion of hard lumps. The degree of carefulness with which the burning and slaking have been conducted may be roughly judged by observing the relative proportions of lumps and powder.

The material remaining as lumps is of three different kinds. First, and in greatest proportion, are fragments of limestone which have not been thoroughly burned in the kiln. Such unburned pieces would be inert if used in the cement. Second, part of the lumps represent fragments of limestone which have been overburned in the kiln and have, therefore, partly clinkered. This is particularly likely to happen if the limestone contained any large proportion of silica or alumina. These partly clinkered lumps, being really poor-grade natural cements, can if pulverized do no particular harm to the slag cement, but on the other hand they cannot do as much good as an equal amount of lime. The third kind of material that may be present in lump form consists of fragments of well-burned lime, which, through accident or carelessness, have not been well slaked. These lumps of quicklime would, if incorporated in the cement, be actively injurious.

The preceding description and discussion of the three classes of material which are likely to remain as lumps in the slaked lime have been intentionally made detailed in order to point out an error in practice committed occasionally at slag-cement plants. It has been seen that the materials composing these lumps are of such a character as to be either useless or actively injurious if used in a slag cement. It should be obvious, therefore, that the only rational method of treatment is to sieve the slaked lime and to reject entirely all the material failing to pass through the sieve. This is the best practice and the method usually followed. Occasionally, however, urged by a false idea of economy or by inaccurate reasoning, the manufacturer saves the material failing to pass the sieve, crushes it, and adds it to the cement at a later stage in the manufacture.

Proportion of lime and slag.—Prost, in consequence of his experiments with various proportions of lime, advocated the proportion, to secure the best results, of from 35 to 40 parts of lime to 100 parts of slag. He also stated that the amounts of lime used in actual practice, for each 100 lbs. of slag were: at Choindez, 40 to 45 lbs.; at Donjeux, 40 lbs.; at Brunswick, 33 lbs., and at Cleveland, 33 lbs. Mahon, in

reporting his experiments for the Maryland Steel Company, states that the best results were secured by the use of 25 parts of lime to 100 parts of slag, by weight. At another American plant the proportions used are 20 lbs. lime to 100 lbs. slag. In the manufacture of slag brick, which is in reality merely a branch of the slag-cement industry, the amount of lime added may fall as low as 10 lbs. to 100 lbs. of slag.

These rules are, of course, purely empirical; and it is time that some better method of calculating the mixture should be presented. This, of course, can be accomplished by the use of the same device which has been previously discussed in connection with hydraulic limes, natural cements, and Portland cements.

Calculating the mixture.—If we determine the Cementation Index * of a series of representative American slag cements, such as is given on page 610, we will find that the value obtained ranges from about 1.6 to 1.9.

Accepting these values as fairly typical the information thus gained can be employed in devising a method for determining accurately the proportions in which any given slag should be mixed with any given lime in order to secure a good slag cement.

Operation 1. **Slag.**—Multiply the percentage of silica in the slag by 2.8, the alumina by 1.1, and the iron oxide by 0.7, add all the products together. From the sum subtract the percentage of lime in the slag plus 1.4 times the magnesia. Call the result "m."

Operation 2. **Limestone.**—Multiply the percentage of silica in the unslaked quicklime by 2.8 the alumina by 1.1, and the iron oxide by 0.7, and add the products together. Subtract this sum from the total percentage of lime (CaO) plus 1.4 times the magnesia. Call the result "n."

Operation 3. Divide $100 \times m$ by $1.7 \times n$. The quotient $\frac{100\,m}{1.7\,n}$, will equal the number of parts of quicklime to be used for each 100 parts of slag. The factor by which n is to be multiplied is here taken as 1.7, a very satisfactory value. Values as low as 1.6 and as high as 1.9 would, however, give the proportions used in practice at various plants.

* As previously explained in detail (pp. 174–175), the Cementation Index is the value obtained from the formula

$$\text{Cementation Index} = \frac{(2.8 \times \text{percentage silica}) + (1.1 \times \text{percentage alumina}) + (0.7 \times \text{percentage iron oxide})}{(\text{Percentage lime}) + (1.4 \times \text{percentage magnesia})}.$$

Example.—Assume that the two raw materials have the following composition:

	Slag.	Limestone.
Silica (SiO_2)	32.2	1.8
Alumina (Al_2O_3)	12.0	1.2
Iron oxide (FeO, Fe_2O_3)	0.6	0.4
Lime (CaO)	48.1	94.0
Magnesia (MgO)	2.3	1.2

Operation 1. Slag.

Silica	$\times 2.8 = 32.2 \times 2.8 =$	90.16
Alumina	$\times 1.1 = 12.0 \times 1.1 =$	13.20
Iron oxide	$\times 0.7 = 0.6 \times 0.7 =$	0.42
		103.78
Lime	$\times 1.0 = 48.1 \times 1.0 =$	48.1
Magnesia	$\times 1.4 = 2.3 \times 1.4 =$	3.22
		51.32

$$103.78 - 51.32 = m = 52.46$$

Operation 2. Lime.

Silica	$\times 2.8 = 1.8 \times 2.8 =$	5.04
Alumina	$\times 1.1 = 1.2 \times 1.1 =$	1.32
Iron oxide	$\times 0.7 = 0.4 \times 0.7 =$	0.28
		6.64
Lime	$\times 1.0 = 94.0 \times 1.0 =$	94.00
Magnesia	$\times 1.4 = 1.2 \times 1.4 =$	1.68
		95.68

$$95.68 - 6.64 = n = 89.04$$

Operation 3.

$$\frac{100m}{1.7n} = \frac{100 \times 52.46}{1.7 \times 89.04} = \frac{5246}{151.4} = \begin{cases} 34.6 = \text{parts unslaked quicklime for each} \\ 100 \text{ parts dry slag.} \end{cases}$$

Pulverizing and mixing.—The greatest differences in practice exist in the processes for grinding and mixing the slag and lime. The statement has been made in several publications that the difference in hardness between dry granulated slag and slaked lime is so great that it is impracticable to pulverize them together in a continuously operated mill. A number of plants, therefore, have installed small discontinuous mills, each of which is charged, locked, operated for a sufficient time to pulverize both constituents of the mixture, and discharged. The disadvantages of this intermittent system are obvious and it seems especially unfitted for American conditions. The statement that no con-

tinuously operated mill was able to handle the mixture seemed inherently improbable, in view of the great variety of material successfully handled by the modern ball and tube mills when operated continuously in Portland-cement practice. Several years ago I referred the question to a leading firm of manufacturers and was informed that nothing in their experience justified the unfavorable conclusion, and that their continuously operated tube mills had successfully pulverized mixtures of slag and lime. It seems probable that the most economical practice would be to send the dried slag through a small crusher, Griffin mill, or ball mill, mixing the crushed slag with lime and completing the mixture and reduction in continuously operated tube mills. Whatever system of reduction is employed, it is necessary that the slag be dried as completely as possible, and, with modern dryers, the amount of moisture in the dried slag can be economically kept well below 1 per cent.

In this connection it may be of service to note the results attained in the grinding of basic Bessemer slag (for use as a fertilizer) by the Pottstown Iron Company. A 2000-mm. Jensch ball mill was there employed. This mill consumed about 13 H.P. Its normal output was 20,000 lbs. in ten hours, though a maximum of 29,000 lbs. in ten hours had been reached on perfectly dry slag. The fineness of the product was such that 95 to 98 per cent would pass a 100-mesh sieve and 70 to 75 per cent a 150-mesh sieve. A West tube mill in use at an American slag-cement plant grinds 8½ barrels per hour of mix to a fineness of 95 per cent through 200-mesh or 10 barrels per hour to a fineness of 90 per cent. In doing this it uses 67 H.P., equivalent to power consumption of 8 H.P. hours or 6.7 H.P. hours, respectively.

Regulation of set.—Slag cements will normally set very slowly compared to Portland cements. As this interferes with their use for certain purposes, many attempts have been made by various treatments to reduce their setting-time. There is, unfortunately, another reason why the manufacturer should desire to hasten the set of his product. Most of the slag cements sold in this country masquerade as Portland, and it is desirable to the manufacturer, therefore, to make such of their properties as are brought out in ordinary tests or analyses approximate to those of true Portland cement. The set of slag cements can be hastened by the addition of puzzolanic materials. Of these, burned clay, certain active forms of silica, and slags high in alumina are the cheapest and most generally obtainable. The most important method of regulation is, in this country at least, the Whiting process, which is followed at two large American plants.

United States Patent No. 544,706, issued in 1895 to Jasper Whiting, covers the use of " caustic soda, potash, sodium chloride, or equivalents or any substance of which the latter are ingredients," added either as aqueous solutions or in a dry state at any stage of the process of slag-cement manufacture. In the specifications accompanying the application for this patent, the patentee states that, in the case of dry caustic soda the amount added will vary from 0.125 to 3 per cent, " depending chiefly upon the use for which the cement is intended." The patent was subsequently conveyed to the Illinois Steel Company, and the process covered by it is used by that company in the manufacture of its " Steel Portland " cement. A license has been issued to the Brier Hill Iron and Coal Company, of Youngstown, Ohio, under which license this company manufactures its " Brier Hill Portland " cement.

The process, as practiced in the slag-cement plant of the Illinois Steel Company, Chicago, Ill., is described as follows: The quicklime used is obtained from the calcination of Marblehead or Bedford limestone and carries less than 1 per cent MgO. On its arrival at the mill it is unloaded into bins, beneath which are placed two screens of different mesh, the coarser at the top. A quantity of lime is drawn upon the upper screen, where it is slaked by means of the addition of water containing a small percentage of caustic soda. As the lime is slaked it falls through the coarse screen onto the finest screen, through which it falls into a conveyor which carries it to a rotary drier. After heating, the resulting slaked and dried lime is carried by elevators to hoppers above the tube mills, where it is mixed in proper proportions with the granulated slag, which has been dried and powdered.

General Practice.—The general practice followed at a number of American and European slag-cement plants will now be described.

A very recent and typical installation is shown in Fig. 156, which gives the plan and elevation of the slag-cement plant of the Stewart Iron Co., at Sharon, Pa. It will be seen that the granulated slag is passed through Ruggles-Coles driers, three of which are in use, and is then elevated to a dry-slag bin on the second floor of the mill. The lime is slaked in an adjoining room, and is also elevated to the second floor. Here the two materials are fed in proper proportions to a screw conveyor, which carries them to a Broughton mixer. The mix is then conveyed to three West tube mills, which deliver the finished product. The Maryland Cement Company,* at Sparrows Point, Md., obtains the slag from the furnaces of the Maryland Steel Company. The slag is dried in Ruggles-Coles driers, and after mixing with the slaked lime

* Lewis, F. H. Cement Industry, p. 184.

is ground in discontinuous West pebble mills. Mahon's experiments preliminary to the establishment of this plant are discussed on an earlier page.

The slag-cement plant of the Illinois Steel Company, Chicago, Ill., obtained its slag from the blast-furnaces of that company. The speci-

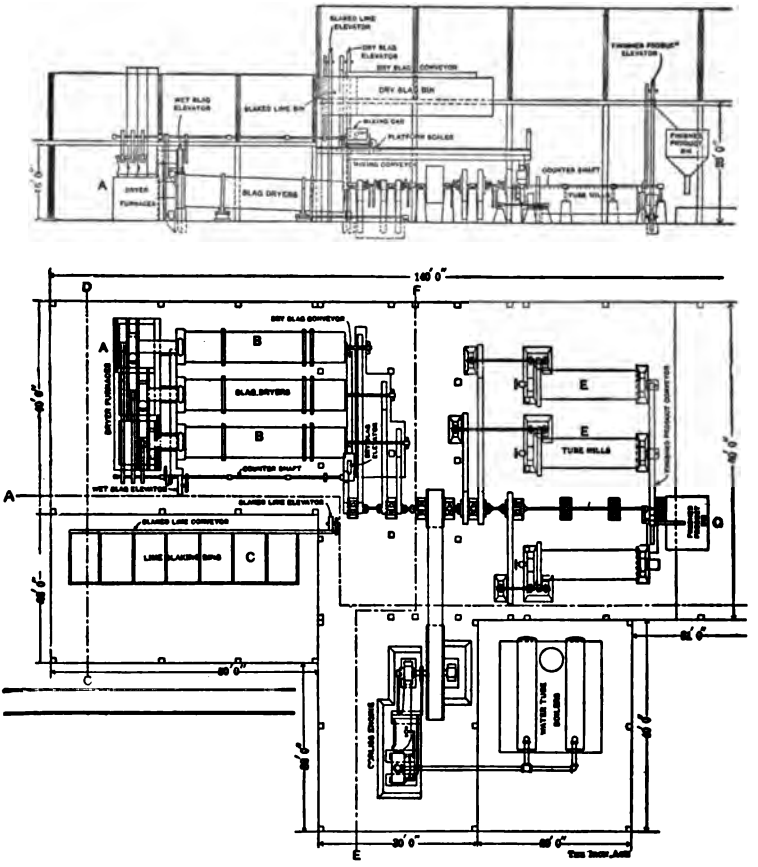

FIG. 156.—Elevation and plan of Stewart slag-cement plant. (The Iron Age.)

fications under which this slag was received, with analyses showing its actual range in composition, will be found on a previous page. After granulation and drying in a specially designed dryer the slag received its preliminary reduction in Griffin mills. Meanwhile the lime had been slaked as described in detail on a previous page (p. 659), caustic soda

being added to regulate the set of the product. The ground slag and this prepared lime were then mixed, and the mixture receives its final reduction in Davidsen tube mills.

At the plant of the Birmingham Cement Company,* at Ensley, Ala., slag is obtained from the furnaces of the Tennessee Coal and Iron Company, located in near-by towns. The slag is granulated at the furnaces. On arrival at the mills, carrying about 40 per cent of water, it is dried in Ruggles-Coles driers. Two of these, of the A2 style, are in operation. After drying, the slag and slaked lime are fed together to West ball mills, four of which are in use, and the mixture is finally reduced in West tube mills.

The Southern Cement Company, at North Birmingham, Ala., dries its slag in a style A2 Ruggles-Coles drier. The dried slag is crushed in a Kent mill. After mixing with the slaked lime, the final reduction takes place in West tube mills. Two brands of slag cement are marketed. One, a normal slag cement, is said to average about CaO 55 per cent, Fe_2O_3, Al_2O_3, 12 per cent, SiO_2, 27 per cent. The other brand is quicker setting and is said to carry about 10 per cent less CaO and about 10 per cent more SiO_2.

At Skinningrove, England, slags were used of a composition varying between the following limits: SiO_2, 30 to 32 per cent; CaO, 30 to 33 per cent; Al_2O_3, Fe_2O_3, 25 to 28 per cent. The slag on issuing from the furnace was run into water; ground, before drying, under edge runners, and dried on iron plates in a drying chamber. The dried material was ground under millstones; sieved and mixed with lime (which had been slaked and screened) in the proportions usually of lime 33 lbs., slag 100 lbs. The resulting cement varied in composition between the following limits: SiO_2, 24 to 26 per cent; CaO, 45 to 47 per cent; Al_2O_3, Fe_2O_3, 20 to 22 per cent.

At Vitry, France, the slag is struck by a jet of water immediately upon issuing from the furnace and carried by it into a masonry storage tank. From this tank the granulated slag is elevated and carried to the mill. Five driers of the style shown in Fig. 162 are employed, the dimensions being slightly different from those used at Choindez. After drying the slag is sieved, to remove the coarser particles, passed through six mills of different types, and again sieved. After having been thus reduced to the proper fineness, it is mixed with the slaked lime in ball mills operated discontinuously; the proportions being about 40 lbs. of lime to 100 lbs. of slag.

* Eckel, E. C. Engineering News, Jan. 23, 1902.

The slag-cement plant at Königshof,* Germany, utilizes slag from the Carl-Emil furnaces. A typical analysis of this slag shows:

	Per Cent.
SiO_2	26.29
Al_2O_3	18.71
FeO	1.80
CaO	49.16
MgO	2.45

The more important constituents commonly vary between the following limits:

	Per Cent.
SiO_2	24 to 27
Al_2O_3	17 " 19
CaO	49 " 54

The slag is granulated, dried, and ground to such fineness that all passes a sieve with 900 meshes per square centimeter, and 85 per cent passes a sieve of 5000 meshes per square centimeter.

The limestone is obtained from quarries at Koneprus, and is burned in continuous shaft kilns. Analysis of the resulting lime shows:

	Per Cent.
SiO_2	12.421
Al_2O_3	2.620
Fe_2O_3	0.883
CaO	81.546
MgO	1.751
CO_2	0.194
Moisture	0.425

From this analysis it would seem probable that the lime is itself somewhat hydraulic. It is carefully slaked, and stored until the slaking is complete, after which it is screened to remove the coarser particles.

The slag and lime are then mixed and ground together in proportions giving a cement of the following typical composition:

	Per Cent.
SiO_2	20.81
Al_2O_3	10.50
Fe_2O_3	1.90
CaO	55.90
MgO	1.41
S	0.58
SO_3	0.91
Loss on ignition	3.50

* Jour. Iron and Steel Inst., vol. 2, 1900, p. 508.

The specific gravity of this cement ranges between 2.80 and 2.90. In all its properties it resembles other slag cements.

Slag cement is made at the Cockerill plant * at Seraing, Belgium, from blast-furnace slags ranging within the following limits:

	Per Cent.
SiO_2	27 to 32
Al_2O_3	12 " 22
CaO	49 " 55

The slag is granulated and dried, the latter taking place at a temperature of about 500° C., and requiring a fuel (coke) consumption of about 9 per cent of the weight of slag dried. The slag is ground so as to all pass a sieve of 76 meshes to the inch, and leave a residue of only 8 to 12 per cent on a sieve of 180 meshes to the inch. Grinding to this fineness requires 25 to 30 H.P. for the production of 450 to 800 kilograms per hour of powdered slag. Lime is burned, slaked by immersion, and stored eight to ten days, at the end of which time it is screened to pass a 76-mesh sieve. It is then mixed with the slag in the proportion of 15 to 20 parts of lime to 100 parts slag.

Costs of Manufacture.—Data regarding the cost of manufacture of slag cement have been recently published.† The figures quoted are said to have been the costs of actual manufacture some years ago at the plant of the Maryland Cement Company. They are as follows, being based on a production of 5000 barrels per month:

	Per Barrel.
Mill force, labor and superintendence	$0.160
125 tons of coal at $3.05 per ton	0.076
3000 bushels of lime at $0.16 per bushel	0.100
900 tons of slag at $0.50 per ton	0.090
Repairs, $100 per month	0.020
Oil and grease, $40 per month	0.007
Contingencies	0.011
	$0.464
Cost of administration	$0.121
	$0.585

These figures seem rather high in some respects. For American plants I should say that the average cost of manufacture should not be over 35 cents per barrel.

* Eng. and Min. Jour., vol. 64, pp. 515–516.

† Boilleau and Lyon. Cost of making slag cement. Municipal Engineering, vol. 26, p. 321. May, 1904.

This would be itemized about as follows:

TABLE 248.

COSTS OF SLAG-CEMENT MANUFACTURE PER BARREL.

	Min.	Max.
Slag	0.04	0.10
Lime	0.07	0.12
Coal	0.03	0.08
Oil, grease, waste, etc	0.005	0.01
Repairs	0.01	0.03
Labor	0.05	0.08
Superintendence, testing, etc	0.03	0.05
	0.23½	0.47

Several American plants have to my knowledge worked quite close to the minimum estimate above given. To this cost should be added, of course, interest on the cost of the plant. If the plant is running steadily this item should not amount to more than two or three cents a barrel.

Production of slag cement.—The slag-cement production of the United States began in 1896, with an output of some 12,000 barrels. The industry grew rapidly for a time, and by 1903 had reached an output of 525,896 barrels, made at eight plants. Until 1907 this position was held, the output of that year being the maximum recorded—557,252 barrels, valued at $443,998. Since that date, however, the American slag cement industry has fallen off rapidly, dropping to 42,678 barrels in 1915. A single plant located in Alabama is still (1922) engaged in slag cement manufacture, but its output is no longer reported separate from natural cement in the official statistics. The European industry, especially in Germany and France, still holds about its place, but shows little signs of further growth.

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CHAPTER XLII.

SLAG CEMENTS: COMPOSITION AND PROPERTIES.

WHILE slag cements are sufficiently like Portland cements to be usually marketed as Portland, certain interesting differences between the two cements are shown on close examination.

Identification of slag cement.—Slag cements may usually be distinguished from Portland cements by their lighter color, inferior specific gravity, and slower set. They show on analysis lower lime and higher alumina percentages than Portlands and usually contain an appreciable amount of calcium sulphide. Owing to the presence of this last-named constituent a briquette of slag cement left for some days in water will show upon fracture a decided greenish tint; if it has been exposed to salt water, this tint will be much more marked, and the odor of hydrogen sulphide will be observed. Two things should be noted, however, in this connection. The presence of sulphides though usual is not a necessary occurrence in slag cements; and, on the other hand, sulphides are occasionally present in Portland cements, being formed from the sulphates in case the flame of the kiln is not sufficiently oxidizing. Another chemical difference between the two types of cement is in the high "loss on ignition" shown by slag cements. This loss, which may range from 4 to 8 per cent, is due largely to the water carried by the slaked lime.

Chemical Composition of Slag Cements.

The ultimate composition of a sample of slag cement will, of course, be brought out by chemical analysis; but the fact that the material is not a chemical compound but merely a mechanical mixture will not be shown in the ordinary report of such an analysis. The average commercial chemist will, moreover,—particularly, if he be accustomed to analyzing Portland cements—make careless and erroneous statements concerning three important points. The three points noted are: (*a*) the condition of the iron which is present, (*b*) the condition of the sulphur which is present, and (*c*) the nature of the "loss on ignition."

A discussion of analytical methods will not be undertaken, as that subject does not properly belong in a treatise of this character. But it may be of value, not only to engineers and slag-cement manufacturers,

but to commercial chemists, to state in some detail what substances are to be expected in examining a normal slag cement. Slag cement when ready for sale is a mechanical mixture of slaked lime and slag. The slaked lime is lime hydrate [$Ca_2(OH)_2$]; the slag may be regarded as a calcium aluminum silicate ($x.CaO$, $y.Al_2O_3.SiO_2$). In addition to the essential ingredients—lime, silica, alumina, and water—contained in these two components of the cement, certain other constituents may occur in small but often interesting percentages. Of these sulphur, iron, magnesia, carbon dioxide, fluorine and soda are those most commonly found.

Analyses of a number of American slag cements are presented in the following table. The Cementation Index of several of these has been calculated, and it will be seen that it gives values (1.59, 1.67, 1.72, 1.87) far above those given by any modern Portland cement:

TABLE 249.

ANALYSES OF AMERICAN SLAG CEMENTS.

	1.	2.	3.	4.	5.	6.
Silica (SiO_2)	27.78	27.20	28.40	28.95	29.80	27.80
Alumina (Al_2O_3)	11.70	14.18	12.80	11.40	12.30	11.10
Iron oxides (FeO,Fe_2O_3)				0.54		
Lime (CaO)	51.71	50.33	51.50	50.29	51.14	50.96
Magnesia (MgO)	1.39	3.22	n. d.	2.96	2.34	2.23
Sulphur (S)	1.31	0.15	1.40	1.37	1.37	1.18
Carbon dioxide (CO_2)	n. d.	4.25	n. d.	3.39	2.60	5.30
Water						
Cementation Index	1.67	.....	.....	1.72		

	7.	8.	9.	10.	11.	12.
Silica (SiO_2)	27.15	28.84	30.98	28.90	29.64	30.20
Alumina (Al_2O_3)	10.80	10.42	11.72	12.72	12.62	11.26
Iron oxides (FeO,Fe_2O_3)	0.90	n. d.	n. d.			
Lime (CaO)	51.57	51.81	51.07	51.19	51.17	51.81
Magnesia (MgO)	2.70	2.21	1.45	1.87	1.98	3.37
Sulphur (S)	1.38	1.42	1.22	1.07	1.13	1.30
Carbon dioxide (CO_2)	3.50	n. d.	n. d.	n. d.	n. d.	n. d.
Water						
Cementation Index	1.59	.....	1.87			

1. "Southern Cross Portland." Birmingham Cement Co., Ensley, Ala. Private communication.
2. "Steel Pussolan." Illinois Steel Co., Chicago, Ill. Lathbury & Spackman, anal. Mfrs. circular.
3–6. "Steel Pussolan." Illinois Steel Co., Chicago, Ill.
7. Maryland Cement Co., Sparrows Pt., Md. Cement Directory, 2d ed., p. 207.
8. " " " " Private communication.
9. "Brier Hill Portland." Brier Hill Coal & Iron Co., Brier Hill, Ohio. Private communication.
10–12. "Stewart Portland." Stewart Portland Cement Co., Sharon, Pa. Private communication.

Table 250 contains the analysis of a number of European slag cements, as given by various authorities. It will be seen that, despite the apparently great variations in practice, the ultimate composition of the finished cement falls within quite narrow limits. The range in composition of a good slag cement may be considered to be about: SiO_2, 22 to 30 per cent; $Al_2O_3+Fe_2O_3$, 11 to 16 per cent; CaO, 49 to 52 per cent. MgO, less than 4 per cent; S, less than 1.5 per cent; ignition loss, 2.5 to 7.5 per cent.

TABLE 250.

ANALYSES OF EUROPEAN SLAG CEMENTS.

Components.	Brunswick, Germany.	Choindes, Switzerland.	Bilbao, Spain.	Donjeux.			Saulnes, France.
SiO_2	25.56	19.5	30.56	23.85	24.85	24.55	22.45
Al_2O_3	11.20	17.5	13.31	13.95	12.10	14.05	13.95
FeO	.....	....	0.25	1.10	3.85	1.85	3.30
CaO	49.70	54.0	45.01	51.40	49.20	49.25	51.10
MgO	.....	....	2.96	1.95	1.75	1.60	1.35
S	.....	....	*4.63	.....	1.30		
SO_3	.....	....	†1.41	0.45	1.35	0.60	0.35
Loss on ignition	.....	....	.....	7.05	5.65	7.75	7.50

* CaS. † $CaSO_4$.

Physical Properties.

Specific gravity.—The specific gravity of slag cements usually ranges from 2.7 to 2.9, as compared with the 3.15 which may be considered a fair average for the specific gravity of a good Portland cement. The slag cements are, therefore, appreciably lighter than Portlands, and more bulk is obtained for the same weight. The following determinations of the specific gravity of three American slag cements have been made in Philadelphia:

Toltec	2.861
Climax	2.888
Penn	2.831

Aside from its use as a method of distinguishing slag cements from Portlands, the determination of the specific gravity of the cement is of little engineering importance. A point which is of engineering importance, however, appears to have been overlooked by experimenters. So far as the writer knows, the relative specific gravities of set briquettes, composed of neat-slag cement and neat-Portland cement respectively, have never been determined. A knowledge of the two values would

be of service, at times, in selecting the type of cement to be used. For some purposes, as in dams, a heavy material is preferable; for others, as in floors, the lighter cement would be better.

Color of slag cements.—Slag cements can usually be distinguished

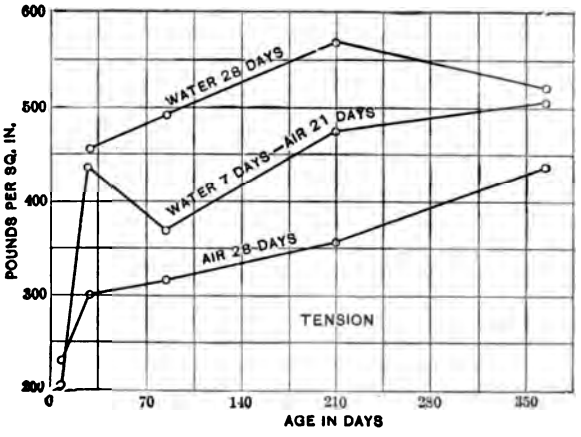


FIG. 157.*—Effect on tensile strength of slag cements of hardening in air or in water. (Tetmajer.)

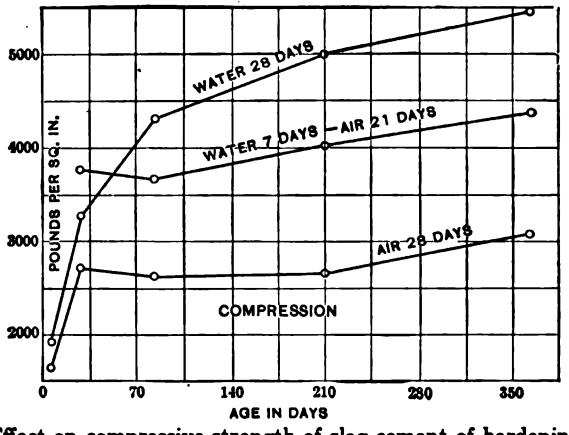


FIG. 158.*—Effect on compressive strength of slag cement of hardening in air or in water. (Tetmajer.)

from Portlands by being much lighter in color and slightly different in tint, while from most natural cements they differ markedly in tint. They are commonly bluish-white to lilac, the exact color of any specimen depending partly on the respective colors of the lime and the

* From Johnson's "Materials of Construction," p. 576.

slag which have been used in its manufacture, but more largely on the relative proportions in which these ingredients have been mixed. Slag cements do not stain masonry; and an imported cement of closely related origin (Meier's Pozzuolan) has long been in favor in this country for architectural uses, because of this non-staining property.

Rapidity of set.—Normally slag cements are slower setting than Portlands. Whether this property is a disadvantage or not will depend on the use to which the cement is to be applied. As before mentioned the rapidity of set increases naturally with the amount of alumina in the slag. Set can be artificially hastened by the addition of puzzolanic material to the cement; burned clay, active forms of silica, slags high in alumina, etc., are additions which are both effective and cheap. The treatment of the cement during manufacture with alkalies to accelerate the set has already been discussed.

Strength.—While slag cements fall below high-grade Portlands in tensile strength, good American slag cements develop sufficient strength to pass the usual specifications for Portlands. Tested neat they do not approximate so closely to the Portlands as they do if tested in 2:1 or 3:1 mortars. Part of this property may be due to the fact that they are in general ground finer than Portlands, especially than foreign Portlands. Prof. W. K. Hatt recently made a large series of tests on American slag cements, and reported that there was no noticeable deficiency in strength of briquettes kept in air as compared with those kept in water. Other investigators have arrived at opposite conclusions; and it is probable that these conflicting results arise from differences in the chemical composition of the various brands tested.

Resistance to mechanical wear.—Slag cements are notably deficient in this property, and are therefore not available for use for the surface of pavement, floors, etc., where this quality must be highly developed; they seem to be well fitted, however, for pavement foundations, or indeed for any work which will not be exposed to dry air, and in which a high strength is not necessary.

Ratio of tensile to compressive strength.—This ratio, which is of importance (as noted in the discussion of Portland cements) seems to be much lower for slag cements than for Portlands. In the case tabulated below, the results of tests show the ratio for slag cement to average 5.3:1, in place of the 10:1 ratio, which is a fair average for Portland cements.

The average value for $\frac{\text{compressive strength}}{\text{tensile strength}}$ for the whole series is 5.3.

TABLE 251.

TENSILE *vs.* COMPRESSIVE STRENGTH OF SLAG CEMENTS.

Mixture.	Test.	7 Days.	28 Days.	7 Days.	28 Days.	7 Days.	1 Month.
Neat cement.....	Tension	441	528	480	503		
" "	Compression	2054.5	...	2470	2830		
	$C \div T$	4.66	...	5.15	5.63		
1 cement, 3 sand.	Tension	170	219	145	200	171	243
" " .	Compression	486.5	...	933	938	1138	1529
	$C \div T$	2.86	...	6.44	4.69	6.65	6.29

List of references on properties and testing of slag cements.— In addition to the list given below, many of the papers cited on pages 607–608 will be found to contain data on the properties and testing of slag cements.

Bonnami, H. Fabrication et controle des chaux hydrauliques et des ciments. 8vo, 276 pp. Paris, 1888.

Candlot, C. Ciments et chaux hydrauliques. 8vo. Paris, 1889.

Detienne, H. Manufacture and properties of slag cement. Revue universelle des mines, Sept. 1897.

Elbers, A. D. Notes on the manufacture and properties of blast-furnace slag cement. Eng. and Mining Journal, vol. 64, pp. 515–516. 1897.

Hatt, W. K. American slag cements. 21st Ann. Rep. Proceedings Indiana Engineering Soc., pp. 45–65. 1901. Also in Engineering News, March 7, 1901.

Le Chatelier, H. Tests of hydraulic materials. Trans. Am. Inst. Min. Eng., vol. 22, pp. 3–52. 1894.

Mahon, R. W. Slag-cement experiments. Journal Franklin Institute, vol. 137, pp. 184–190. 1894.

May, E. Slag cement: Its production and properties. Stahl und Eisen, March and April, 1898. Abstract in Iron Age, Sept. 1, 1898.

Prost, M. A. Note sur la fabrication et les propriétés des ciments de laitier. Annales des Mines, 8th series, vol. 16, pp. 158–208. 1889.

Redgrave, G. R. Manufacture and properties of slag cement. Proc. Institution Civil Engineers, vol. 105, pp. 215–230. 1891.

Rohland, P. Influence of catalysers on velocity of hydration of cements, plasters, and limes. Zeitschrift anorg. Chemie, vol. 31, pp. 437–444. Abstract in Journal Soc. Chem. Industry, vol. 21, p. 1233. 1901.

U. S. Army Board of Engineers. Report on Steel Portland Cement. 8vo, 112 pp. Washington, 1900.

Whiting, J. The definition of Portland cement. Engineering Record, July 30, 1898.

Anon. The distinction between slag and Portland cements. Engineering Record, July 9, 1898.

Specifications for slag cements.—So far as known, the only American specifications for slag cement were those prepared and published in 1902 by the Engineer Corps, U. S. Army. These are reprinted below.

SPECIFICATIONS FOR PUZZOLAN CEMENT.

Engineer Corps, U. S. A., 1902.

(1) The cement shall be a Puzzolan of uniform quality, finely and freshly ground, dry, and free from lumps, made by grinding together without subsequent calcination granulated blast-furnace slag with slaked lime.

(2) The cement shall be put up in strong sound barrels well lined with paper, so as to be reasonably protected against moisture, or in stout cloth or canvas sacks. Each package shall be plainly labeled with the name of the brand and of the manufacturer. Any package broken or containing damaged cement may be rejected, or accepted as a fractional package, at the option of the United States agent in local charge.

(3) Bidders will state the brand of cement which they propose to furnish. The right is reserved to reject a tender for any brand which has not given satisfaction in use under climatic or other conditions of exposure of at least equal severity to those of the work proposed, and for any brand from cement works that do not make and test the slag used in the cement.

(4) Tenders will be received only from manufacturers or their authorized agents.

(The following paragraph will be substituted for paragraphs 3 and 4 above when cement is to be furnished and placed by the contractor:

No cement will be allowed to be used except established brands of high-grade Puzzolan cement which have been in successful use under similar climatic conditions to those of the proposed work and which come from cement works that make the slag used in the cement.)

(5) The average weight per barrel shall not be less than 330 lbs. net. Four sacks shall contain 1 barrel of cement. If the weight as determined by test weighings is found to be below 330 lbs. per barrel, the cement may be rejected, or, at the option of the engineer officer in charge, the contractor may be required to supply, free of cost to the United States, an additional amount of cement equal to the shortage.

(6) Tests may be made of the fineness, specific gravity, soundness, time of setting, and tensile strength of the cement.

(7) **Fineness.**—Ninety-seven per cent of the cement must pass through a sieve made of No. 40 wire, Stubb's gauge, having 10,000 openings per square inch.

(8) **Specific gravity.**—The specific gravity of the cement, as determined from a sample which has been carefully dried, shall be between 2.7 and 2.8.

(9) **Soundness.**—To test the soundness of cement, pats of neat cement mixed for five minutes with 18 per cent of water by weight shall be made on glass, each pat about 3 inches in diameter and $\frac{1}{2}$ inch thick at the center, tapering thence to a thin edge. The pats are to be kept under wet cloths until finally set, when they are to be placed in fresh water. They should not show distortion or cracks at the end of twenty-eight days.

(10) **Time of setting.**—The cement shall not acquire its initial set in less than forty-five minutes and shall acquire its final set in ten hours. The pats made to test the soundness may be used in determining the time of setting. The cement is considered to have acquired its initial set when the pat will bear, without being appreciably indented, a wire $\frac{1}{12}$ inch in diameter loaded to $\frac{1}{4}$ lb. weight. The final set has been acquired when the pat will bear, without being appreciably indented, a wire $\frac{1}{24}$ inch in diameter loaded to 1 lb. weight.

(11) **Tensile strength.**—Briquettes made of neat cement, after being kept in air under a wet cloth for twenty-four hours and the balance of the time in water, shall develop tensile strengths per square inch as follows:

After seven days, 350 lbs.; after twenty-eight days, 500 lbs.

Briquettes made of one part cement and three parts standard sand by weight shall develop tensile strength per square inch as follows:

After seven days, 140 lbs.; after twenty-eight days, 220 lbs.

(12) The highest result from each set of briquettes made at any one time is to be considered the governing test. Any cement not showing an increase of strength in the twenty-eight-day tests over the seven-day tests will be rejected.

(13) When making briquettes neat cement will be mixed with 18 per cent of water by weight, and sand and cement with 10 per cent of water by weight. After being thoroughly mixed and worked for five minutes the cement or mortar will be placed in the briquette mold in four equal layers and each layer rammed and compressed by thirty blows of a soft brass or copper rammer, $\frac{3}{4}$ of an inch in diameter or $\frac{7}{10}$ of an inch square, with rounded corners, weighing 1 lb. It is to be allowed to drop on the mixture from a height of about half an inch,

When the ramming has been completed the surplus cement shall be struck off and the final layer smoothed with a trowel held almost horizontal and drawn back with sufficient pressure to make its edge follow the surface of the mold.

(14) The above are to be considered the minimum requirements. Unless a cement has been recently used on a work under this office, bidders will deliver a sample barrel for test before the opening of bids. If this sample shows higher tests than those given above, the average of tests made on subsequent shipments must come up to those found with the sample.

(15) A cement may be rejected in case it fails to meet any of the above requirements. An agent of the contractor may be present at the making of the tests, or, in case of the failure of any of them, they may be repeated in his presence. If the contractor so desires the engineer officer in charge may, if he deems it to the interest of the United States, have any or all of the tests made or repeated at some recognized testing laboratory in the manner herein specified, all expenses of such tests to be paid by the contractor. All such tests shall be made on samples furnished by the engineer officer from cement actually delivered to him.

French specifications and use.—Various French government bureaus permit the use of slag cement for certain definite purposes. The chief points in the specifications covering such use are as follows:

1. Slag cements are made of an intimate mixture of dry granulated slag and slaked lime. They must come from a mill designated by the contractor and accepted by the chief engineer.

2. Slag cement should leave less than 3 per cent on a sieve of 900 meshes to the square centimeter; and be without appreciable residue on the sieve of 324 meshes to the centimeter.

3. The set, immersed in ordinary water, should commence within three hours and be completed in less than twenty hours.

4. Cylindrical testpieces of neat cement should be kept in a humid atmosphere until set is complete. After this they should be placed in water and its temperatures should be raised to 100° C. in thirty minutes, being retained at that temperature for six hours. The Vicat needles used in this test should not show a separation of over 10 mm.

5. Slag cement mortar tests should show at least 9 kg. at end of seven days and 16 kg. (per square centimeter) at end of twenty-eight days.

6. Slag cements can be employed only in foundations or other works entirely underground. Their use is forbidden in works hardening in air; it is also forbidden in reinforced concrete.

CHAPTER XLIII.

SLAG BRICKS AND SLAG BLOCKS.

UNDER the names of " slag brick," " slag tile," " slag block," " scoria brick," etc., two very different products have been included by various writers. Both products are made from blast-furnace slag, but the two classes differ so greatly in their methods of manufacture and properties that it seems necessary to describe them separately. This has accordingly been done, the names " slag bricks " and " slag blocks " being supplied to the respective classes. As here used, the term " slag brick " will be confined to those bricks, tiles, etc., which are made by mixing slaked lime with ground slag, molding the mixture by hand or in a brick-machine, and drying or steaming the product. The term " slag blocks," on the other hand, will be applied to the products made by pouring molten slag into brick-shaped molds.

Slag Bricks.

The structural products included in this chapter under the head of " slag bricks " include those which are made by mixing granulated slag with slaked lime or with slag cement, molding the mixture in a brick-press or by hand, and drying it in the air, with or without the use of steam. It will be noted that all the raw materials used in this industry are the same as those utilized in the manufacture of slag cement; and indeed the manufacture of slag bricks may be considered as being merely a specialized phase of the slag-cement industry.

Though the slag-cement industry of the United States is in a fairly satisfactory condition no serious attempt seems to have been made to prepare slag bricks, tile, pipes, etc., on a commercial scale. Small amounts of slag bricks have been made for use about the mills and furnaces and for the local market, but apparently no attempt has been made to extend the manufacture.

Methods of manufacture.—The slags used are basic blast-furnace slags, but a somewhat greater range in composition is allowable for slag bricks than when the slags are to be used in cement-manufacture. The analyses quoted in the present chapter may be regarded as fairly

representative of the class of slags used in slag-brick manufacture. It will be seen that the silica ranges from 22.5 per cent to 35 per cent; the alumina and iron oxide together, from 16.1 per cent to 21 per cent; the lime, from 40 per cent to 51.5 per cent. As in slag cements, sulphur is an objectionable constituent. Much of it, fortunately, is removed during the process of granulating the slag.

The general steps in slag-brick manufacture may be stated as follows: Slags of proper composition are granulated by being run into a stream of cold water immediately upon issuing from the furnace. This causes the slag to break up into little porous particles, thereby greatly reducing the expense of subsequent grinding: Granulation also confers hydraulic properties on the slag, and removes part or all of its contained sulphur. The granulated slag is dried and pulverized. Powdered slaked lime is added in sufficient quantity to bring the total calcium oxide content of the mixture up to about 55 per cent. This mixing, as well as the previous burning and slaking of the lime, must be carefully and thoroughly done in order to prevent subsequent disintegration of the bricks. Usually, during or after the mixing, a small amount of water is added. The mixture is then molded into shape, either by hand or in a brick-machine. After shaping, the bricks are dried in the open air, this usually taking six to ten days in dry weather. In the best practice, the bricks are retained for several months, after drying, in order that they may be well hardened before marketing.

Though over 90 per cent of the total production of slag brick is at plants following the above methods, three other methods may be briefly noted. At a few plants the granulated slag is mixed, without drying, with the unslaked lime; the slag furnishing sufficient water to slake the lime. Slaking in this way is very imperfectly done, however, and the practice should never be followed if high-grade bricks are expected. At a few other plants, notably at the Bilbao plant described below, slag is mixed with slag cement instead of with lime. At certain English plants, also noted below, the slag bricks are hardened in steam cylinders like the cylinders used in lime-sand brick manufacture.

Slag bricks vary in color from a grayish white to dark gray. They weigh less than clay bricks of equal size, are said to require less mortar in laying up, and are at least equal to clay bricks in crushing strength. The product usually seems to find a ready market, though, of course, the low value of the material, relative to its bulk and weight, precludes long railroad transportation.

Methods at special plants.—Slag bricks were manufactured at the Cleveland Slag Works, Middlesborough, England; but the manufac-

ture has been discontinued for some years. At this plant the wet granulated slag was mixed with "selenitic lime" (see Ch. XV) instead of with common lime. The selenitic lime was composed of 80 per cent quicklime, 10 per cent gypsum, and 10 per cent iron oxide. About 670 lbs. of this selenitic lime was sufficient for 1000 bricks. The mixture of slag and lime was pressed to shape in a brick-press; and the bricks were stacked in sheds for a week, to harden enough to handle well. After this they were stacked in the open air for five or six weeks more, when they were ready for use. The bricks were dull-gray in color, and very hard and tough. Buildings constructed of them over twenty years ago are still in a good state of preservation. The manufacture of slag bricks at these works was given up for reasons not connected with the technical value of the product, which seems to have acquired an excellent local reputation.

At Vitry, France, the manufacture * of slag bricks and pipes is carried on in connection with the manufacture of slag cement. The bricks are made by mixing 60 parts of slaked lime with from 250 to 300 parts of granulated slag. Sufficient water is added to this mixture to make a firm paste, from which the bricks are molded in hand- or steam-presses. These slags are found to be especially useful for foundations or basement work, pavements, etc. "Facing brick" are made from a similar mixture, with the addition of some fine sand. Sewer pipes are made from a mixture consisting of 500 kgs. of slag cement and 1 cu. m. of sand. This mixture is made into a stiff mortar, and forced into steel molds by iron rammers. The molds are removed as soon as the ramming has finished. The pipes are then dried for three days, after which they are immersed in water for twenty-four hours. They are then stacked in the factory ground for several months, after which they are ready for market.

Slag bricks are manufactured † on a large scale at Kralovedvoor, near Prague, Bohemia. The slags normally used at this plant vary in composition within the following limits:

	Per Cent.
Silica (SiO_2)	25.8 to 27.0
Alumina (Al_2O_3)	17.3 " 19.3
Iron oxide (FeO)	1.5 " 1.7
Manganese oxide (MnO)	0.0 " 0.1
Lime (CaO)	51.4 " 51.5
Magnesia (MgO)	0.4 " 2.5
Sulphur (S)	1.3 " 1.8

* Engineering News, Jan. 1, 1897.

† Engineering and Mining Journal, April 16, 1898.

As the slag issues from the furnaces it is run into an inclined iron trough in which cold water is flowing. In addition to granulating the slag, a considerable portion of the sulphur is removed in this way. The granulated slag is run into tanks, from which it is carried to the mixing floor, as required, by conveyors. Here the slag is dumped into mixers, together with thoroughly slaked lime in a pasty condition. The lime is obtained by the calcination of a limestone of the following range in composition:

	Per Cent.
Silica (SiO_2)	0.2 to 0.6
Alumina (Al_2O_3) and Iron oxide (Fe_2O_3)	0.2 " 0.8
Lime carbonate ($CaCO_3$)	97.0 " 98.4
Magnesium carbonate ($MgCO_3$)	0.9 " 1.9

The mixture is then molded into shape under pressure in a brick-machine with a capacity of 1000 bricks per hour. These bricks are taken to the drying house, where they remain about eight days, at the end of which time they are sufficiently hard to stand transportation. In the size usually made, the dry bricks weigh about 4.75 kgs. each, and will stand a pressure of 18 kgs. per square centimeter. In color they vary from nearly white to grayish. Cement and mortar adhere to them as well as to clay bricks.

Occasionally bricks are made at this plant from slags of the following average composition, derived from the smelting of a manganiferous ore different from that commonly used at these furnaces:

	Per Cent.
Silica (SiO_2)	33.00
Alumina (Al_2O_3)	18.67
Iron oxide (FeO)	1.00
Manganese oxide (MnO)	4.25
Lime (CaO)	40.00
Magnesia (MgO)	2.33
Sulphur (S)	1.33

Bricks made from this slag are dark colored, owing to the comparatively large percentage of manganese present. More lime must be used, in proportion to the slag, and the bricks made from this slag require a longer time to dry and harden than is needed by those made from the ordinary slag.

Slag bricks are made at Ekaterinoslav,* Russia, from blast-furnace slags showing the following range in composition:

* Engineering and Mining Journal, 1896.

	Per Cent.
Silica (SiO_2)	22.5 to 35.0
Alumina (Al_2O_3)	14.0 " 15.0
Iron oxide (Fe_2O_3)	1.1 " 3.3
Manganese oxide (MnO)	0.0 " 0.3
Lime (CaO)	45.0 " 51.0
Magnesia (MgO)	tr. " 1.4
Sulphur (S)	0.3 " 0.4
Loss on heating	2.3 " 7.5

The slag is granulated, sieved on a revolving screen, dried, and ground in a ball mill. Lime is slaked and sieved. Enough of this slaked-lime powder is added to the slag to bring the lime (CaO) content of the mixture up to about 55 per cent. With slags of the range in composition above indicated, this would require the mixture to consist of from 5 to 12 parts of lime to 100 parts of slag. The mixing is carried on in a screw mixer, and the powdered mix is then pressed into brick in a dry press. On issuing from this press the bricks are set aside to harden, and at the end of six days are usually hard enough for use. Their tensile strength is about 312 lbs. per square inch; and the crushing strength varies from 1250 to 5600 lbs. per square inch; both, of course, increasing with age. The bricks are gray in color, well shaped, weigh less than stone, and require little mortar in laying up. They withstand temperature changes well, and are particularly well adapted for use in damp situations or under water.

Toldt has described the manufacture of slag bricks at Bilbao, Spain, where the blast-furnace slag from the Vizcaya furnaces is used. Slag cement is made by mixing three parts of granulated and dried slag with one part powdered slaked lime, and grinding this mixture in a ball mill. The bricks are then made by mixing one part by volume of this cement with four parts of wet granulated slag, and pressing this mixture into shape in a brick-press. A Belgian form of press with twelve molds is used. This turns out twenty bricks per minute, with thirteen workmen.

It will be noted that in a slag brick made in this fashion the strength of the brick must be almost entirely derived from the slag cement used in the mixture, for the uncrushed slag will be almost inert.

Hardening in steam-cylinders.—A new method of slag-brick manufacture has recently been introduced * in England. In this process the use of lime is dispensed with (except when slags carrying less than 35 percent CaO are used), while a hardening cylinder is employed exactly as in the manufacture of lime-sand brick (see pp. 136–140). The slag is

* Sutcliffe, E. R. Utilization of blast-surface slag. Amer. Mfr. and Iron World, vol. 74, pp. 555–563, May 5, 1904.

allowed to cool normally; it is then broken up and fed to an edge-runner mill, where it is crushed and ground, and falling thence into a deep pit under the mill, it is collected by an elevator and thrown on a 10-mesh screen. All capable of passing this goes to the mixer, the coarser particles being rejected and returned to the mill for further grinding. "The ground slag is moistened in the mixer with from 5 to 10 per cent of water, and is then delivered by the mixer into the brick-making machine, where it is molded into bricks under great pressure, the pressure employed being from 100 to 150 tons on each brick. As the bricks are made they are stacked onto steel platform-wagons made to carry from 700 to 800 bricks. The loaded wagons are allowed to stand for twelve hours, to allow the bricks to take a slight initial set, after which they are run into the steel chamber, and the bricks are here subjected to the action of steam at a pressure of from 105 to 120 lbs. per square inch. Ten hours under this treatment is sufficient to harden the bricks and render them on withdrawal ready for building purposes.

"It is necessary that the machinery employed should be of a very strong and durable character. For effecting the grinding an edge-runner mill is most suitable, as it is not easily put out of order by the iron which is often found in the slag in large pieces. The roller rims and false bottom should be of steel, preferably manganese steel; and the perforated grate should also be of steel, the rollers should be made of a suitable weight, depending upon the hardness of the slag—generally from three to five tons each. Their width should not exceed 12 inches.

"A specially designed brick-making machine is employed. This consists of a rotating table containing the molds, a feeding-pan, and powerful toggle-press. As the table revolves, the molds pass alternately under the feeding-pan where they are fed with the charge of material, then under the press, and a further rotation brings the mold over the ejecting plunger and the brick is discharged ready for removal. The machine is capable of exerting a pressure on each brick of 150 tons, and is fitted with a simple contrivance to insure the corners of the bricks being well pressed up. Its operation is first to give the material in the mold at a top pressure by means of a wedge-shaped plunger, forcing the material well into the sides and corners of the mold, and a final pressure from below, which completely presses out the indentation made by the wedge-shaped plunger and gives a good finish to the sides and corners of the brick. The necessity of this arrangement will be apparent when it is understood that ground slag does not become plastic under pressure as does ordinary clay, and that a material when filled into a

mold by gravity naturally piles in the center, and if directly pressed would produce bricks of greater density in the center than at the sides.

" The hardening-chamber is like a boiler without flues, 45 feet long by 6 ft. in diameter. It contains 6000 bricks, and must be capable of withstanding the pressure of steam, which is used for their indurating. One end of the chamber is removable and held in place by hinged bolts threaded on to a back ring, the joint being made by a projection on the cover fitting into a recess in the shell, the bottom of the recess being filled with ordinary red rope packing. The chamber will permit of two steamings per day—one during the daytime and the other at night. Hence each chamber with high-pressure steam serves for 12,000 bricks per day.

" The brick wagons must be strongly constructed, as any deflection of the platform might tend to crack and spoil the bricks, which in the green state require some care in handling. It is necessary that roller or ball bearings be used for the axles, as under the action of the steam any oil or grease would be burnt out of ordinary bearings.

" It will be noted that no binding material whatever is mixed with the slag. The process is really the production of a concrete. In grinding the slag fine enough to pass a 10 per inch mesh a very large proportion of it is reduced to a fine dust, which acts as a hydraulic cement, the coarser particles forming the aggregate. Where the slag is very hard, and consequently only a small proportion of dust is produced, it is necessary to reduce a portion in a ball mill or other suitable fine-grinding machine. The precise action which takes place during the hardening is difficult to determine; but evidently the result is due to a combination being effected between the free lime found in all limy slags and the silica and alumina.

" It may be assumed that the silicious compounds in the slag become soluble in the presence of heat and moisture, in which condition it is readily attacked by the free lime present in the slag.

" With some slags high-pressure steam gives better results than low-pressure, besides requiring less time to effect the hardening. In speaking of high-pressure steaming, it is to be understood that this refers to any pressure above the atmosphere and low pressure to at or under this. With other slags low pressure is quite as effectual as, and in some instances is better than, high pressure. To determine which is the most suitable process is a question for experiment with the particular slag. Where low-pressure steaming is adopted the chambers may either be made of thin sheet steel or tunnels may be constructed of brickwork.

In the author's experiments a steel high-pressure chamber was used steaming up to 150 lbs. pressure per square inch and for low pressure a chamber constructed of brickwork. In general, for low-pressure steaming for about forty hours, and for high-pressure steaming twenty hours, will be found most suitable and convenient. The author has not formed a definite opinion as to what element in the slag causes the different effect in the action of high- and of low-pressure steam, but is inclined to think that it is principally due to the proportion of sulphur in the slag. During the steaming some sulphur is driven out of the bricks, and the final hardening does not seem to be completed until this volatile or unfixed sulphur is driven out or combined. It is probable that the sulphide of calcium present is slowly being split up, the hydrogen of the water combining with the sulphur forming sulphuretted hydrogen, and the oxygen with the calcium forming lime. By subjecting the slag to steam, thus keeping it moist and hot at the same time, this action is accelerated.

"Generally slags high in sulphur can be hardened best under prolonged low-pressure steam, and in one or two instances no hardening effect was produced by high-pressure steam, whereas low-pressure steam produced the desired effect. From this it would seem that the chemical action is only accelerated up to a certain temperature, and that at a higher temperature a different effect is produced; or it may be that at a higher temperature the action is too violent, causing an expansion and separation of the particles without actually producing cracks or disintegration of the bricks, but sufficient to prevent the final combination. Seemingly the presence of this unfixed sulphur retards the action of the lime on the silicates and aluminates, and only when it is finally driven off can the full combination be effected.

"In the case of a slag which falls to powder on exposure to the atmosphere a grinding-mill is unnecessary; and with some slags of this character it is only necessary to moisten and then press it into bricks and harden as before. Again, with others it would be necessary to grind a portion to dust in a ball mill before the setting could be obtained. In the former case the slag powder would consist of a fine dust mixed with coarser particles, and in the latter case it would be like a fine even-grained sand without any really fine dust.

"The slag used for brickmaking should preferably be new; but it has been found that a slag which had been exposed for twenty years still possessed setting properties when acted upon by steam. One of the bricks exhibited was made in the summer of 1901 from slag which had been exposed to the atmosphere for over twenty years.

"In the case of a slag which disintegrates on exposure to the atmosphere it would not be wise to use it directly after it has cooled unless the ground-moistened slag is permitted to stand until the free lime is thoroughly hydrated. This could be effected in silos erected directly over the brickmaking machine; and twenty-four hours in this condition would be sufficient. In general the better plan would be to allow the slag to stand for about ten days before being used, as in such cases the grinding would be facilitated by the disintegrating.

"The slag for brickmaking should preferably be cast in thin layers capable of being easily broken up in sizes suitable for being passed into the grinding-mill, rendering a stone-breaker unnecessary.

"The bricks are almost perfect in form, there being no twisting or distortion produced by the induration, and in strength and other qualities they will compare with the best qualities of clay bricks.

TABLE 252.

CRUSHING STRENGTH OF INDURATED SLAG BRICKS.

No. of Specimens.	Dimensions in Inches.	Cracked at Tons per Sq. Ft.	Crushed at Tons per Sq. Ft.	Remarks.
1	9×4⅛×2⅞	227	340	
1	9×4⅛×2⅞	303	375	Not completely crushed
1	9×4⅛×2⅞	227	375	Not completely crushed
1	9×4⅛×2⅞	246	370	

"Objections have been raised against granulated slag bricks on account of their porosity, which ranges in some cases as high as 15 per cent. No objections of this kind can be raised against these indurated slag bricks, the absorption being remarkable low as shown in Table 253.

"The bricks before testing were thoroughly dried at 212° and then immersed for twenty-four hours.

TABLE 253.

POROSITY OF SLAG BRICKS.

No.	Dimensions in Inches.	Weight before Immersion.	Weight after Immersion.	Gain in Weight.	Per Cent.
1	9×4⅛×2⅞	8 lbs. 10 oz.	9 lbs. 1 oz.	7 oz.	5.07
2	9×4⅛×2¼	8 lbs. 12 oz.	9 lbs. 4 oz.	8 oz.	5.71

"These bricks were tested by burning them in an ordinary continuous brick kiln, and a brick treated in this way withstood the fire successfully and is still a good hard brick, the only change being in the color, which is now a light buff. During the burning the loss in weight averaged 6 ounces, which equals 4.47 per cent; and the absorption

after burning was 16 ounces, or 11.9 per cent, after twenty-four hours' immersion.

" The following is the estimated cost of production, based on a production of 10,000 bricks per day of ten hours:

Labor.	£	s.	d.
1 man at grinding-mill at 6d. per hour	0	5	0
2 men at brickmaking machine, taking off, at 6d. per hour	0	10	0
1 youth attending to moistening of material	0	3	6
4 wheelers and stackers at 6d. per hour	1	0	0
1 foreman	0	6	0
	2	4	6

Cost in labor per 1000 bricks, say 4s. 6d.

" To this must be added the cost of getting the slag to the machinery, wear and tear, depreciation, and such charges as may be added for power and steam.

" As regards the slag, this should be run from the furnaces on to a level floor and then broken up and taken to the machinery. This will mean a little extra cost over that of running the slag in wagons and depositing it in balls on the slag heap; but 6d. per ton should cover the whole cost of casting the slag in this way and running it to the machinery. Wear and tear on machinery will necessarily be high, considering the wearing action of the slag. This will be well provided for at 1s. 6d. per 1000 bricks.

" As to power and steam, this would be generated from the furnace gases, and if not used for this purpose might be considered as wasted; but assuming this at the value of coal, if such were used we should require 2½ tons of coal per day, which, at 10s. per ton, works out at 2s. 6d. per 1000 bricks. If we allow 6d. per 1000 for generation, we get 3s. per 1000 bricks.

" The cost of a complete plant such as described would be about £3000, including buildings and all requirements. Taking depreciation at 7½ per cent on the whole, and reckoning on 300 working days, we get 15s. per day, or 1s. 6d. per 1000 bricks.

Summary of Cost of Production per 1000 Bricks.

	s.	d.
Cost of labor	4	6
Slag at 6d. per ton (4 tons)	2	0
Wear and tear	1	6
Power and steam	3	0
Depreciation	1	6
Oils, sundries, etc	0	6
Total cost of production	13	0

"The above calculation is based on only producing 10,000 bricks per day. The plant would be capable of making up to 12,000 per day; so that by only calculating on this reduced output sufficient allowance is made for unforeseen losses. If a larger plant were installed the cost could be very considerably reduced; on a plant producing, say, 20,000 bricks per day, the cost per 1000 should not be more than 10s. to 11s.

"This refers more particularly to limy slags; but in the case of slags not so rich in lime, hydrated lime can be added to the ground slag and the hardening effected in the same way, but in such cases the cost of production is increased by the cost of this added lime.

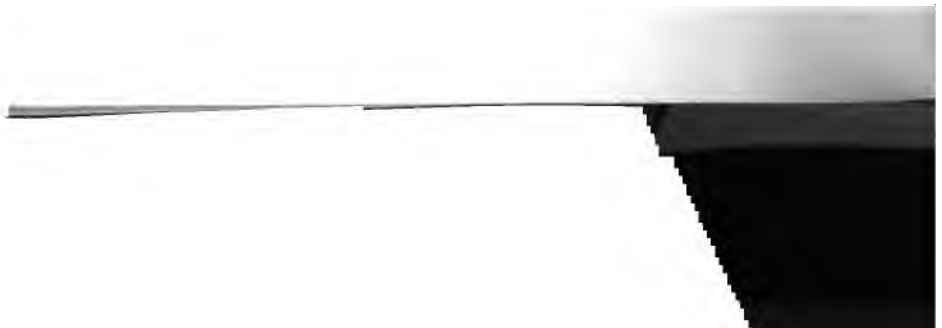
"As before pointed out, most limy slags have setting properties without being steamed; and with slags containing from 40 to 48 per cent of lime, bricks may be made by merely grinding and pressing the material and permitting the bricks to stand out in the open air, the same conditions being observed as in making granulated slag bricks, but this method is not so satisfactory as the hardening by steam. In many slags there is a proportion of soluble salts which tend to spoil the bricks when allowed to harden naturally by appearing as efflorescence. This in some cases is so violent that the outer crust will be forced away from the brick; but the same effect does not happen when they are steamed, the steaming either turning the salts into a stable compound or driving them off.

"These bricks will withstand the weather equally with a high-class clay brick. Bricks have been exposed to the weather the whole winter and no effect whatever is noticeable upon them. They have been soaked, then frozen, and afterwards put into hot water without deterioration."

Slag Blocks.

Under this heading will be considered all these products ("slag blocks," "slag tiles," etc.) made by running molten slag, direct from the furnaces, into molds of proper shape. The term *slag block* will be employed as a general but distinctive name for this class of products in order to distinguish them from the *slag bricks* made by mixing granulated slag with slaked lime, which have been discussed in previous sections of this chapter.

Slag blocks, if properly made, are stronger than slag bricks. They are, however, impervious to air and moisture; and on that account are not good building materials, for dwellings constructed of them are apt to be damp and unhealthful. Their chief uses are for foundations



or for paving blocks, for the latter of which they are particularly well adapted.

Many smelters and furnaces have made small amounts of slag blocks for local use. For the past thirty years or so a considerable quantity have been made in the Lehigh iron district of Pennsylvania, their earliest recorded use being in the slag-block pavements laid in Philadelphia about 1876.

The properties required in a slag block to be used for paving work are density, resistance to abrasion, toughness, and roughness of surface. These properties are found to vary with the chemical composition of the slag, the rapidity with which the slag is allowed to cool, and the character of the molds used. By properly varying the last two factors, slags of almost any composition can be utilized in this industry.

The three requisite properties first mentioned—i.e., density, resistance to abrasion, and toughness—vary directly with the rate of cooling, the slowly cooled blocks being the best. Blocks cast in sand molds and heavily covered with loose sand, cool very slowly, and give very much better results than those cast in iron molds. Slowness in cooling, however, requires much greater storage space than if rapid cooling is practiced; and casting in sand molds demands a higher grade of workmanship than casting in iron molds.

The roughness of surface—or non-slipperiness—of blocks intended for paving use is highly important, especially as slipperiness has been the chief defect charged against slag blocks, which defect is prevalent in blocks cast in iron molds. In English practice it has been overcome by casting the block in a double size mold, having a projection inside which results in a notch on the slag block. The block is, after coating, split apart at this notch, and the rough fracture-surface of each half is laid uppermost in paving. This method of avoiding slipperiness adds considerable to the labor cost of the blocks, and is therefore not well adapted to American practice. Slag blocks cast on a sand bed are free from the defect noted (slipperiness); or at least it can be avoided if sufficiently coarse sand be used.

Slag blocks manufactured by the Tees Scoria Brick Company, of Middlesborough, England, have been somewhat extensively employed * as street pavement in Rotterdam. Holland clay bricks, limestone blocks, and porphyry bricks are employed in the same city, and will be useful for comparision with the slag blocks. The foundation, in all cases, is simply a bed of sand, carefully packed. The thickness or

* Streets and Highways in Foreign Countries. Special Consular Report, vol. 3, p. 190, Washington, 1897.

depth of pavement laid on this varies, according to the paving material, as follows: Clay bricks, 4½ inches; slag blocks, 5 inches; limestone or porphyry blocks, 6 inches. The cost of material and laying per square yard is: Clay bricks, 62½ cents; limestone blocks, 62½ cents to $1.25; slag blocks, $1.25; porphyry blocks, $1.56. No data as to proportions of each pavement in use, or durability of the different types, are available. The adjunct director of public works of Rotterdam stated that for light traffic the clay-brick pavements were regarded as the best; for medium traffic, slag blocks or limestone; for heavy traffic, porphyry blocks.

The manufacture of slag blocks from copper slags at Mansfeldt, Saxony, has been described * in detail by Egleston. The industry, as carried on in this locality, presents certain features of interest which warrant a somewhat lengthy abstract of the paper cited.

The slags used are high in silica, ranging from 40 per cent to 60 per cent. When cooled rapidly, they form a dark colored brittle glass, but if cooled with great slowness the product becomes gray and crystalline. These slowly cooled slags are both hard and tough, and therefore serviceable in the manufacture of structural material. The process employed at Krug Hutte is as follows:

The slag, as it comes from the furnaces, is carried in slag wagons to the molding ground, where the bricks are cast. The bed of the molds is sand, which has been sieved to remove coarse particles.

The bed is then carefully gone over with a shovel, which is pressed into it an inch or so to make the sand soft. It is then smoothed over with the shovel, and into the corners a piece of iron 0.18 meter to 0.20 meter long, and 0.15 meter wide is laid, inclined so as to facilitate the passage of the slag in the slag-runners which go round the whole space.

The molding-bed is then so divided by iron partitions pushed down into the sand as to give the size of blocks required. These partitions have several round holes, about 0.05 meter in diameter, near their tops, to permit the entrance of slag. Previous to use, the partitions are washed with clay and sprinkled with sand to prevent the slag from sticking to them. Around each of the molds thus formed is a space 0.20 meter wide, through which the slag flows. When all the partitions are in place, the bottom of each mold is made flat by pressing down into it a piece of sheet iron (of the same size as the compartment), attached to a handle.

* School of Mines Quarterly, vol. 12, pp. 112–117.

When the molds are ready slag is brought from the furnace in slag wagons, and allowed to flow through the interspaces and into the molds. When the slag has about half filled a mold, a little sand is thrown on it to prevent too rapid cooling. When the molds are entirely full they are covered with about a foot of sand and allowed to stand for forty-eight hours. At the end of this time the slag is cool, the sand is shoveled off, and the iron partitions removed.

During rainy weather the molding ground is kept covered with boards until the slag is ready for pouring, and as soon as this operation is finished the molds are again covered with boards.

The blocks are usually cubes, 0.15 meter on the edge, though larger sizes and different shapes are occasionally cast. The material which has solidified in the spaces between the molds is broken up for use as road metal.

At Koch Hutte similar processes are employed. Large blocks, however, are cast in cast-iron molds, with a cover that is shut down in order to compress the slag. Similar work is carried on at Kupferkammer Hutte.

Analyses of typical slags from the Mansfeldt district are given in Table 254.

A very interesting example of the manufacture of slag blocks or tiles from a copper blast-furnace slag has been described * by Braden as having been seen in operation at a furnace located near Santiago de Chile. His description is as follows:

The slag and matte are tapped from the blast-furnace into a slag-pot. After settling for a few moments the slag is poured from ladles into molds which are 6 inches square and 1 inch deep. The molds after being filled with slag are placed on a hearth which has a movable cover, and covers are placed on the molds as well as on the hearth. A very light heat is kept up, so that the slag cools very slowly. When it appears black the molds are lifted from the hearth and the slag tiles are dumped into cold water. The tiles thus made are very light and portable. When laid they have proven to be tough and durable. For this manufacture a slag carrying a considerable excess of iron has been preferred. The tiles are sold for from $30 to $60 (pesos Chilenos) per thousand.

* Trans. Am. Inst. Min. Engrs, vol. 26, pp. 52–53. 1896.

TABLE 254.

ANALYSES OF SLAG, MANSFELDT.

	Krug Hutte.	Koch Hutte.	Eckhardt Hutte.	Kupferkammer Hutte.	
Year	1888	1888	1888	1881	1881
	Per Cent.	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Lime	18.35	23.187	21.51	19.29	20.29
Magnesia	6.732	2.22	0.847	3.23	4.37
Alumina	14.825	17.001	16.525	16.35	15.67
Iron oxide	4.725	4.643	2.768	10.75	8.73
Manganese oxide	0.697	0.328	0.744		
Nickel and cobalt oxides	0.063	tr.	tr.		
Zinc oxide	1.165	0.692	0.934	1.26	1.11
Lead oxide	0.232	0.118	tr.		
Copper oxide	0.289	0.277	0.3	0.75	0.67
Silica	47.63	48.465	46.39	48.22	50.0
Fluor					
Total	97.708	96.931	90.018	99.85	100.84

	Kupferkammer Hutte.		Sangerhausen Hutte.	
Year	1881	1888	1881	1881
	Per Cent.	Per Cent.	Per Cent.	Per Cent.
Lime	19.50	19.15	33.10	23.40
Magnesia	8.02	3.677	1.67	0.87
Alumina	18.17	17.636	4.43	7.83
Iron oxide	5.89	7.213	4.37	7.47
Manganese oxide	.....	0.827		
Nickel and cobalt oxides	.....	0.038		
Zinc oxide	3.57	2.056		
Lead oxide	.....	0.065		
Copper oxide	0.23	0.333	0.25	0.30
Silica	48.38	46.81	53.83	57.43
Fluor	0.99	.....	2.09	1.97
Total	99.75	97.802	99.74	99.27

Slag blocks have been manufactured at a Montana copper smelter by a process which contrasts strongly with the practice at Mansfeldt and Santiago. The copper slag was poured into iron molds built up by putting together iron plates of proper form. The process was carried on in the open air and no covering of any kind was placed on the blocks. The slag in consequence cooled very rapidly. Though the product was, therefore, not as dense or tough as that secured at Mansfeldt, the Montana practice effected a great saving of time and space.

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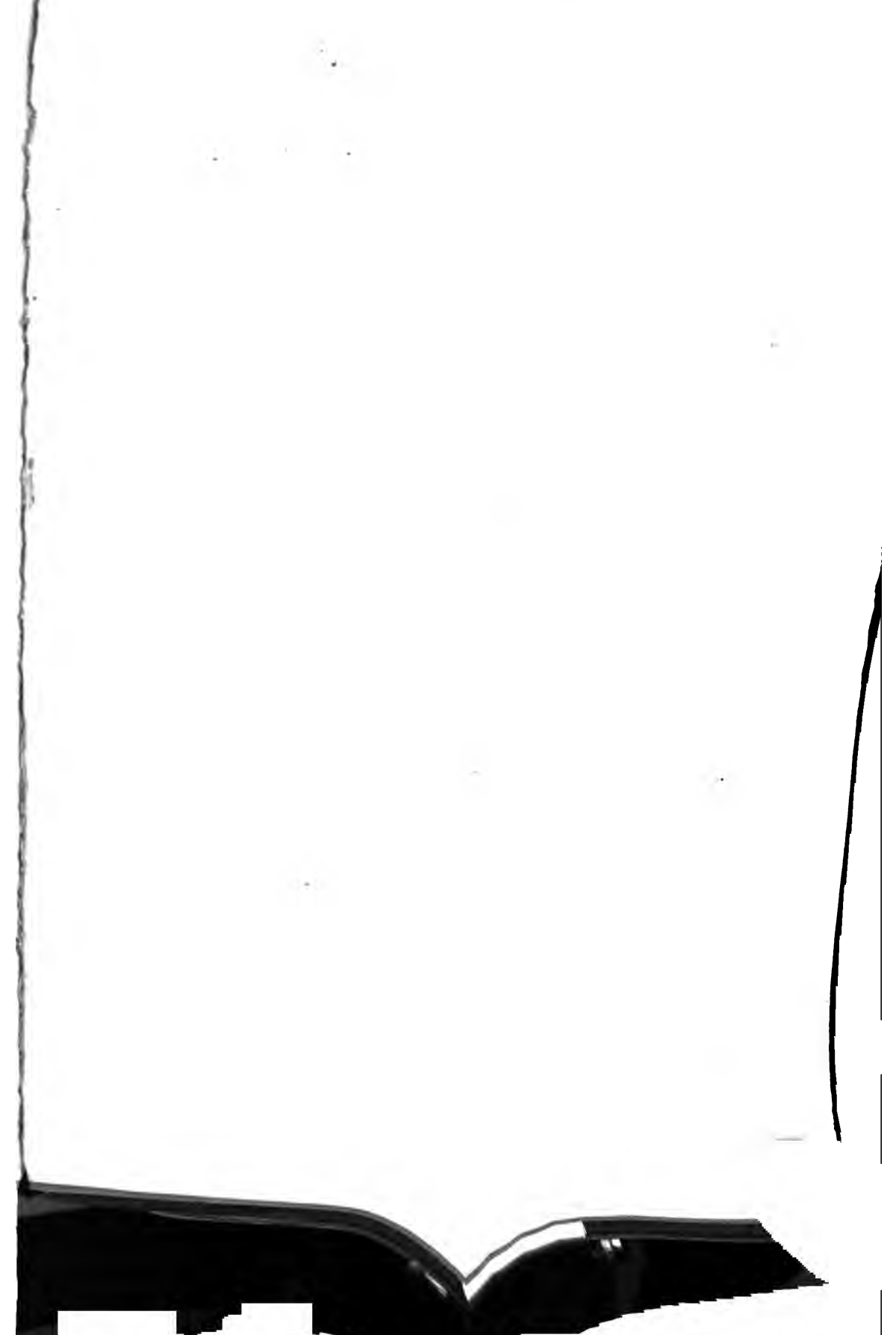

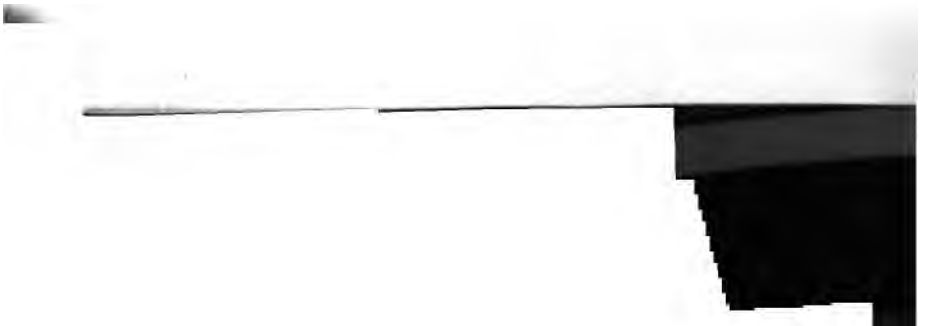
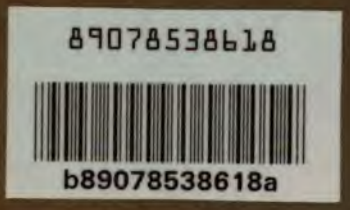
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